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16. ABSTRACT

This technical handbook provides guidance to the designer of cover systems for existing uncontrolled hazardous waste sites. It also presents sources of technical information to aid regulatory personnel in evaluating cover designs. Comprehensive coverage is given to the following subject areas: site characterization, materials used in cover systems, design of a cover system, cover construction, and construction quality control. Two case histories are described.

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PREFACE

This technical handbook is one of a series of publications being issued to implement CERCLA, otherwise known as the Superfund law. These documents discuss technical matters involved in implementing the National Contingency Plan (NCP) for dealing with releases of hazardous substances.

This document is intended to provide information and guidance for the benefit of cover designers and regulatory personnel concerned with cover installations at uncontrolled waste sites. It is not intended to replace the services of a qualified design engineer, nor does it address every conceivable waste-site cover problem. The carrying out of remedial actions at uncontrolled waste sites is an evolving field, and experience gained with actual cover installations over the coming years will provide increased knowledge and may well lead to changes in some recommended practices.

Although this technical handbook is not meant to address policy, CERCLA actions should, as a matter of recent Agency policy, comply with applicable or relevant standards of other statutes unless one of five exceptions applies in a limited number of instances (see the Federal Register, February 12, 1985 Proposed Revision to the NCP, for discussion of this policy and the five exceptions). For covers at Superfund sites, this policy generally means that the RCRA technical requirements contained in 40 CFR 264.310 should be met.

The specific requirements under 40 CFR 264.310 are presented here to assist the user of the technical handbook in the evaluation of proposed covers at uncontrolled hazardous waste sites. The regulatory requirements (40 CFR 264.310) specify that final cover be designed and constructed to:

(1) Provide long-term minimization of migration of liquids through the closed landfill.

(2) Function with minimum maintenance.

(3) Promote drainage and minimize erosion or abrasion of the cover.

(4) Accommodate settling and subsidence so that the cover's integrity is maintained.

(5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

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Recommended guidance has been developed for meeting these five regulatory requirements although alternative designs could also meet the five regulatory requirements. The ability of alternative designs to meet the five regulatory requirements would have to be demonstrated with more detail than the recommended design.

The RCRA guidance for covers specifies that the cover should consist of the following as minimum:

- Vegetated top cover
- Middle drainage layer
- Low permeability bottom layer
  - > 20 mil synthetic - upper component (may be optional)
  - $\geq$ 2 ft clay layer - lower component

Detailed guidance on each component is as follows:

A) Vegetated Top Cover

- o minimum 24 in. thick
- o should support vegetation that minimizes erosion without continued maintenance
- o planted with persistent species - no roots that will penetrate beyond the vegetative and drainage layers
- o top slope, after settling and subsidence, of between 3-5% - if > 5% use USDA Universal Soil Loss Equation to demonstrate a soil loss of < 2.0 tons/acre/yr.
- o surface drainage system capable of conducting runoff across cap with no problems.

B) Middle Drainage Layer

- o minimum 12 in. thick
- o saturated conductivity not less than 1×10^{-3} cm/sec
- o bottom slope of at least 2 percent
- o designed to prevent clogging - overlain by a graded granular or synthetic fabric filter
- o discharge flows freely

- The granular or fabric filter is used to prevent plugging of the porous media with fine earth particles carried down from the vegetated layer.

- To prevent fluid from backing up into the drainage layer, the discharge at the site should flow freely (the edge of the unit should drain freely, e.g., into surface runoff ditch).

C) Low Permeability Bottom Layer

- upper component

  - o at least 20 mil synthetic (may be optional)
  - o bedding layer at least 6 ft thick - no coarser than unified soil classification system sand (sp)
  - o final upper slope at least 2%
  - o be located wholly below the average depth of frost penetration in the area of interest

- lower component

  - o at least 2 ft of soil recompacted to a saturated conductivity of not more than 1×10^{-7} cm/sec
  - o soil emplaced in lifts not exceeding 6 inches before compaction.

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ABSTRACT

This Technical Handbook provides guidance to the designer of cover systems for existing uncontrolled hazardous waste sites. The Handbook also presents sources of technical information to aid regulatory personnel in evaluating cover designs. A cover over an uncontrolled hazardous waste site acts as a roof, deflects precipitation, minimizes percolation and leachate formation, and thus prevents or minimizes future ground-water contamination. To estimate the amount of leachate expected from a given cover design, it is necessary to perform a water-balance analysis.

A cover design is site-specific and requires a good site investigation report, which is normally prepared as part of the Hazardous Substance Response process. A cover system can be properly designed only after decisions regarding certain basic considerations, such as design life of the system and future use of the site, have been made.

The majority of the materials used in any cover system are likely to be soils, which are best classified by the Unified Soil Classification System (USCS). Soil properties important in cover applications include gradation, Atterberg Limits, density, and permeability. Standardized tests for these and other soil properties are described and/or technical manuals referenced. Soils may be stabilized or modified by the use of soil additives.

Several types of materials other than soils may be used in cover systems. Some parts of a cover system require impermeable materials; other parts require permeable materials. Materials for impermeable applications include asphalt, cement, and synthetic membranes known as "geomembranes." Materials for permeable applications include various waste or residual substances from industrial processes, drainage supplies such as pipes and tiles, and synthetic fabrics known as "geotextiles." Tests and criteria are available for judging the suitability of all these materials.

To meet the requirements for various functions and attributes, the most efficient cover system is composed of layers. If gases are produced by organic decay within the wastes, a gas-permeable layer above the wastes, with suitable venting mechanisms, may be required. One or more permeable filter layers is necessary where materials of contrasting gradation are placed in direct contact with one another in the presence of water; otherwise fines may migrate and block the pores of the coarser material. A foundation or buffer layer is necessary to serve as a platform on which to build the rest of the system. The hydraulic barrier layer may be composed of either relatively impervious natural soils, amended soils, or a geomembrane. The drainage layer intercepts percolating water and provides a path for it to a disposal outlet. A biotic barrier layer stops animals and plant roots from penetrating and

thereby disrupting the hydraulic barrier. The surface layer must provide for vegetative support, stabilize the surface against erosion, aid in dewatering the cover through evapotranspiration, and provide an aesthetically pleasing appearance. An effective surface water management plan is essential to control surface runoff. Elements of this plan are discussed.

During construction, the site preparation phase involves establishment of site security, clearing and grubbing operations, and establishment of support facilities, access roads, and soil stockpiles. Equipment used during the subsequent cover construction phase includes both conventional earth moving machinery and specialized equipment such as may be required in geomembrane installation. During the site closure phase, institutional care and maintenance are performed and the site is monitored to ascertain whether the cover system is performing as intended.

Quality control and assurance for cover system installation depends on an effective construction organization, appropriate observation, sampling and testing methods, and good documentation. There should be good communication between the design, construction, and inspection groups, and clearly defined responsibilities for each. Observations are made continuously of site preparation, excavation, foundation preparation, barrier installation, drain installation, and other activities. Sampling of installed cover materials should be done on a planned, systematic basis. From the many test methods available, quality control test methods should be chosen on a site-specific basis, considering the merits and limitations of each method. Complete documentation is the backbone of any effective quality assurance program.

Two existing cover installations are presented as examples.

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CHAPTER 1

INTRODUCTION

1.1 Background

Effectively covering an uncontrolled hazardous waste site may be one of the most efficient remedial measures to limit the spread of contamination. The cover may be a part of a total system, or it might be the only measure used; in either case most of the geotechnical principles involved are the same. This handbook is an attempt to present those principles in a way that will be useful to the cover designer.

The term "uncontrolled" refers to existing waste-disposal sites that have not been managed in accordance with any uniform set of standards. Presently operating and future disposal sites fall within the purview of the Resource Conservation and Recovery Act of 1976 (RCRA), and are thus controlled sites. They must be designed and operated in accordance with published regulatory standards. Uncontrolled sites include older sites of all descriptions. Some may have been operated conscientiously and according to the best technical practice available at the time, but ranging from this optimum are all grades of random and haphazard disposal, sometimes with little or no regard for environmental consequences.

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) addressed itself to the cleanup of hazardous materials sites where contamination is being released into the environment. Hazardous materials, as defined in Section 101 of CERCLA, comprise those substances that, when released into the environment, threaten the public health or welfare or the environment itself. The fund established by CERCLA to pay for such cleanups is commonly known as "Superfund." CERCLA, and the regulations based on it, govern accidental releases that may occur from time to time, but they also govern releases that have taken place and continue to take place from uncontrolled waste-disposal sites. Cover, among other remedial measures, may be effective in stopping or controlling these long-term releases.

As mandated by CERCLA, the Environmental Protection Agency (EPA) developed an updated National Contingency Plan (NCP), which was published in the Federal Register on 16 July 1982 (pages 31202-31243). The NCP establishes certain systematic procedures. One of these procedures is a Hazard Ranking System, necessary to establish priorities among the various problem sites that may be eligible for a Superfund response. Another procedure is for Hazardous Substance Response - Subpart F of the NCP. The response procedure comprises

seven distinct phases, as follows: I - Discovery and Notification; II - Preliminary Assessment; III - Immediate Removal; IV - Evaluation and Determination of Appropriate Response; V - Planned Removal; VI - Remedial Action; VII - Documentation and Cost Recovery.

Cover, as a Remedial Action, falls under Phase VI of the response procedure. "Remedial Action," defined at length in the NCP (Section 300.6), refers to measures that are of a permanent nature and that serve to prevent or mitigate the migration of a release into the environment. Section 300.70 of the NCP provides a lengthy list of possible remedial measures, which is reproduced in Table 1-1.

Cover falls under "Surface Seals" in Table 1-1, under the more general heading of "Surface Water Controls." Table 1-1 identifies a wide variety of available remedial methods. The decision as to what measures to use will be made during Phase IV of the NCP's response process, Evaluation and Determination of Appropriate Response. Cover may never be used as the sole remedial measure, and indeed good practice demands that all the alternatives listed under Surface Water Controls be taken into account, if a cover is to function effectively. Cover and other surface water controls will commonly be used with other systems, (e.g., for ground-water and gas-emissions control). Perhaps it will seldom be necessary to choose between cover and other systems. Nevertheless, relative to other remedial measures, cover has certain desirable attributes, which should be borne in mind. Cover is basically a simple system, easy to understand and relatively easy to design effectively. It uses simple materials and common construction techniques. Being at the ground surface, it can be observed and inspected at any time, and is accessible and easy to repair. It is a preventive measure, tackling the leachate problem by preventing leachate formation. In the hydrologic cycle that leads to leachate formation and migration, cover occupies an upstream position; thus cover deals mainly with fresh water, which is more benign and whose properties are better known and understood than the downstream leachate solutions, as regards their effect on materials. While these advantages might not warrant selecting cover in preference to another measure, they might indeed warrant emphasizing cover as a prime component of the remedial system.

1.2 Purpose and Scope

The purpose of this Technical Handbook is to provide guidance to the designer of a cover system for an uncontrolled hazardous-waste site. It is also intended that the Handbook be a source of technical information for regulatory personnel to aid them in evaluating any such design submitted for approval.

Subjects discussed in this Handbook include:

- Functions that the cover system must perform.
- Materials suitable for constructing the system.
- Pertinent material test methods.

TABLE 1-1

POSSIBLE REMEDIAL METHODS

a. General
b. Engineering Methods for On-Site Actions
   1. Control Technologies
      i. Air Emissions Control
         A. Pipe Vents
         B. Trench Vents
         C. Gas Barriers
         D. Gas Collection Systems
         E. Overpacking
      ii. Surface Water Controls
         A. Surface Seals ("covers")
         B. Surface Water Diversion and Collection Systems
            1. Dikes and Berms
            2. Ditches, Diversions and Waterways
            3. Chutes and Downpipes
            4. Levees
            5. Seepage Basins and Ditches
            6. Sedimentation Basins and Ponds
            7. Terraces and Benches
         C. Grading
         D. Revegetation
      iii. Ground Water Controls
         A. Impermeable Barriers
            1. Slurry Walls
            2. Grout Curtains
            3. Sheet Pilings
         B. Permeable Treatment Beds
         C. Ground Water Pumping
            1. Water Table Adjustment
            2. Plume Containment
         D. Leachate Control
            1. Subsurface Drains
            2. Drainage Ditches
            3. Liners
      iv. Contaminated Water and Sewer Lines
         A. Grouting
         B. Pipe Relining and Sleeving
         C. Sewer Relocation
   2. Treatment Technologies
      i. Gaseous Emissions Treatment
         A. Vapor Phase Adsorption
         B. Thermal Oxidation
      ii. Direct Waste Treatment Methods
         A. Biological Methods
            1. Treatment via Modified Conventional Wastewater Treatment Techniques
            2. Anaerobic, Aerated, and Facultative Lagoons
            3. Supported Growth Biological Reactors
         B. Chemical Methods
            1. Chlorination
            2. Precipitation, Flocculation, Sedimentation
            3. Neutralization
            4. Equalization
            5. Chemical Oxidation
         C. Physical Methods
            1. Air Stripping
            2. Carbon Adsorption
            3. Ion Exchange
            4. Reverse Osmosis
            5. Permeable Bed Treatment
            6. Wet Air Oxidation
            7. Incineration
      iii. Contaminated Soils and Sediments
         A. Incineration
         B. Wet Air Oxidation
         C. Solidification
         D. Encapsulation
         E. In Situ Treatment
            1. Solution Mining (Soil Washing or Soil Flushing)
            2. Neutralization/Detoxification
            3. Microbiological Degradation
c. Offsite Transport for Storage, Treatment, Destruction, or Secure Disposition
   1. General
      i. More Cost Effective
      ii. Create New Hazardous Substances Management Capacity
      iii. Necessary to Protect Public Health, Welfare, or the Environment
   2. Contaminated Soils and Sediments Removal from Site
      i. Excavation
      ii. Hydraulic Dredging
      iii. Mechanical Dredging
d. Provision of Alternative Water Supplies
   1. Individual Treatment Units
   2. Water Distribution System
   3. New Wells in a New Location or Deeper Wells
   4. Cisterns
   5. Bottled or Treated Water
   6. Upgraded Treatment for Existing Distribution Systems
e. Relocation

Source: NCP, sec. 300.70. This list is not to be considered inclusive of all possible methods of remedying releases.

- Components and features necessary for the system to perform its functions.

- Construction methods and equipment.

- Quality-control methods to insure that the system is actually installed as designed.

The reader should be aware of two important things that this Handbook does not and cannot do. One concerns site specifics - topography, climate, available materials, etc. The designer must formulate an appropriate design for any given site based on these specific conditions. The Handbook cannot offer specific designs tailored to individual cases.

Secondly, the Handbook does not address questions of risk assessment and cost-benefit analysis. These highly important matters involve public-health, economic, political, and social questions as well as technical ones. Often, the technical design must await resolution of nontechnical questions. It is important that both designer and regulator be aware of this fact.

1.3 Cover Functions and Attributes

Cover may perform a number of functions, as listed in Table 1-2. Along with functions are listed necessary attributes, which the cover must have to accomplish its functions. Attributes pertain mainly to the cover's own durability and permanence. The purpose of good design is to provide these attributes while assuring the performance of the desired function or functions.

Of the functions addressed in Table 1-2, vectors and blowing litter and dust are present at operating municipal waste-disposal sites, but much less commonly so at Superfund sites. Aesthetics and site reclamation are important, and must be factors in the design process, but they must be considered secondary to controlling hazardous materials or conditions. The relative importance of the remaining functions may be judged by an examination of published descriptions of Superfund sites. The threats at such sites are groundwater contamination, surface-water contamination, soil contamination, bottom-sediment contamination, air pollution, and the hazard of fire or explosion.

Soil contamination at a Superfund site will have already occurred. Any present or future spread of such contamination relates to the movement of liquids or gases. Any action to control liquid movement will address the soil-contamination problem as well.

Contaminated bottom sediments represent transported contaminated soil. Prevention of erosion of contaminated soil will prevent its further transportation. Placing any durable cover over contaminated soil will prevent the erosion of the soil. However, the question of whether liquid contamination is occurring will still have to be faced.

TABLE 1-2

COVER FUNCTIONS AND ATTRIBUTES

Functions
Prevention or Minimization of Percolation
Promotion of Aesthetics
Suppression of Vectors
Containment of Gases
Suppression of Fire Danger
Prevention of Blowing Litter or Dust
Promotion of Site Reclamation

Necessary Attributes
Water Erosion Resistance
Wind Erosion Resistance
Stability Against Slumping and Cracking
Stability Against Slope Failures
Resistance to Cold-Weather Distress
Resistance to Disruption by Animals or Plants

Note: This table is adapted from Lutton, Regan, and Jones (1979).

9 3 1 2 9 0 4 0 9 2 2

Air pollution would occur if the waste substances were to give off gases or vapors, or if the obnoxious substance were a powder and the wind were to disperse it as a dust. Gases and vapors may evolve from a chemical reaction in which they are produced or merely by the evaporation of a substance with high vapor pressure (a volatile substance). The former of these mechanisms is more powerful and threatening. The reaction may be one in which two or more reacting substances come into contact, or it may be a biochemical one involving the decay of organic material. Reaction-produced gases will develop high enough pressures to force their way to the surface. Vapors from a buried body of volatile liquid would not generate enough pressure to force their way to the surface. Such a vapor might, however, saturate a dry, porous soil above it, and as days of higher and lower barometric pressure succeed one another, the soil might "exhale" the noxious vapors in menacing quantities. Also, noxious vapors can reach the surface entrained with reaction-produced gases. Where either the quantities or the nature of waste-produced gases is sufficiently threatening, a system to control them must be provided.

Fires or explosions, both of which are rapid chemical reactions, require one or more reactable substances and an initiation mechanism. Usually one of the substances is atmospheric oxygen. Virtually any cover that excludes air and immobilizes fluids will prevent fires and explosions.

The two remaining threats, contamination of ground and surface waters, represent by far the greatest real problem for which cover offers a solution. At 85 percent of the first 160 Superfund sites publicly announced by EPA, water contamination was reported as a problem. Water contamination was five times more commonly mentioned than any other problem, and at those sites where more than one threat was recognized, water contamination was usually recognized as the dominant one. The prevention of water contamination, particularly ground-water contamination, is the most difficult and challenging assignment for a cover system. Virtually any cover system that satisfactorily handles the water-contamination problem also handles the other threats.

For these reasons, this Handbook concerns itself predominantly with covers whose principal function is to minimize water contamination. Essentially, this means preventing or minimizing infiltration and percolation. With one proviso, however; the problem of gas evolution is recognized, and systems are presented to handle it where it is present (See Section 4.3).

1.4 Different Types of Waste Sites

Along with different functions, there exist different types of waste sites. For purposes of RCRA, EPA recognizes four types of waste sites: landfills, surface impoundments, waste piles, and land treatment facilities. In landfills, which are probably the most common uncontrolled waste disposal sites, waste was dumped in excavations beneath the ground surface, commonly in abandoned sand, gravel, or borrow pits. At surface impoundments, liquid wastes are contained in some sort of holding basin: a pit, pond, or lagoon. Waste piles are simply sites where waste has been dumped in a mound above the ground surface. Land treatment is a relatively new technique whereby wastes

are spread over an area and intimately mixed into the upper zone of the soil. Many sites will not fit neatly into one category. For instance, a waste dump in a ravine or on a hillside might be a borderline case between a landfill and a waste pile. A given overall site may have one or more surface impoundments in close proximity to waste piles or landfills. At some old uncontrolled sites, liquid wastes may have been poured directly onto the ground. It is difficult to classify this practice into any of the above categories.

The different types of sites may have different requirements with respect to cover. The cover function will not differ, but rather the cover's attributes, and certain aspects of design, will certainly vary. A waste pile, for instance, being above the ground surface, necessarily has side slopes, and is potentially subject to slope failures. This problem generally does not affect other types of waste sites. Slopes mean fast-running water, which means erosion; thus, waste piles are degraded by water erosion, as rills and gullies form. A critical and difficult problem for landfill and surface impoundment cover systems is slumping and subsidence. This problem means that the foundation on which the cover is placed must be strong. Surface impoundments, being liquid, present a particular problem in this regard. If the liquids are not removed, not only must they be stabilized by being solidified, taken up by an absorbent, or otherwise immobilized, but the material must be strengthened so that it will support a cover, without slumping, over a long term. Landfills are low-lying, in contrast to waste piles. Thus landfills are less exposed to rill erosion on the slopes, but they have greater requirements for active drainage as a matter of design. Water tends both to collect in low spots and to run in channels through them. The channelized flow presents an erosion threat, and the collection means that larger quantities of water are present and a quantitatively larger leachate-prevention problem must be faced.

No two uncontrolled waste sites will be precisely alike. In all cases, good engineering judgment, brought to bear on specific conditions at the site, will be the most important factor in effective cover design. Therefore, this Handbook gives few hard and fast rules, but stresses general principles and attempts to point out where and when a particular principle is likely to come into play.

1.5 Concept of Cover as a Roof

Because prevention or minimization of infiltration has been identified as cover's primary function, it is logical to compare cover to a roof, which performs precisely the same function for a building. Certain attributes of a roof will relate to the attributes or properties required of cover, and certain aspects of roof performance may instructively be kept in mind when considering cover in relation to other remedial techniques. Six aspects common to covers and roofs are as follows:

(1) Impermeable layer. The heart of a roof is an impermeable member which deflects rain or meltwater and prevents it from entering the building. A cover likewise must possess a substantially impermeable member to prevent or retard the entrance of water.

(2) Slope considerations. An important attribute of a roof is its pitch or slope. A certain pitch is necessary to promote prompt runoff. Too low a pitch prevents the use of shingled construction, and a zero pitch (flat roof) demands an especially sturdy and defect-free membrane and necessitates positive means for disposing of the water. Flat roofs are notorious for leakage problems. All of these factors have counterparts with respect to cover. The flatter a cover, the more demand is placed on it by a given amount of precipitation.

(3) Handling of effluent drainage. The water that a roof intercepts must be disposed of. It may be allowed to flow or drip off the edge, it may be collected in a gutter or downspout, or in a suitable climate (warm, sunny, windy) it may simply be allowed to evaporate. Effective operation of the roof demands that this disposition mechanism work properly. Just so with covers: good drainage will minimize the demand placed on cover, and maximize its effectiveness and its life.

(4) Mechanical stability. A roof must be properly supported, and sturdy enough not to warp or bend. Its components must be strongly enough assembled not to be torn apart by wind, frost, or other agents of weathering. Analogously, a cover system must be so designed and built that mechanical strains do not lead to its failure. Desiccation of materials within a cover system might lead to such mechanical strains.

(5) Chemical stability. If a roof is in a special service, as where exposed to a corrosive atmosphere above or below, it may fail unless special protective measures are employed. Similarly a cover system at a hazardous waste site, because of the substances with which it is in contact, may require special attention to insure its chemical stability.

(6) Long-term stability. Some slate or tile building roofs may endure for centuries. Other roofs of cheap synthetic materials may have to be replaced within a few years. Not only the materials, but the construction standards and design, affect a roof's longevity. It is surely likewise with cover systems: materials, construction, and design will all affect their long-term performance.

The analogy with roofs may be carried one step further by mention of structures in which roofs serve their purpose without the assistance of walls and floors. Such structures are "bohios" (Spanish; thatched-roof huts without walls) in tropical rural societies, equipment sheds on farms, and even carports. These structures do not furnish complete protection from the elements, and if rain occurs accompanied by wind, their protected contents do indeed get wet. Nevertheless, these structures perform their intended function of deflecting the great majority of precipitation. The analogy with cover would relate to a cover system not accompanied by either a bottom seal beneath the waste deposit nor an impermeable side wall around it. If the great majority of precipitation could be deflected from passing through the deposit, the result might be a sufficient beneficial effect (through removing the driving force behind waste migration), to control the problem at hand, even without these other protective devices.

1.6 Ideal Versus Real Covers

The ideal cover system would be simple, effective, reliable, durable, stable in contact with all kinds of waste, aesthetically attractive, and inexpensive, and would require no maintenance nor attention after it was placed. In reality, certain requirements conflict with others. Virtually all realistic materials are stable in the presence of some waste substances, but not of others. Vegetation can both be aesthetically attractive and perform valuable functions to aid both the cover's integrity and its effectiveness; however, left unmanaged, vegetation will inevitably tend to disrupt and ultimately destroy the cover. Virtually nothing is totally weathering and erosion resistant; the more such resistance is desired, the more will have to be paid for it.

Thus, in real covers, certain inevitable trade-offs have to be faced. In this Handbook, we attempt to make these trade-offs clear and to present the factors that enter into them so that the designer may weigh them judiciously against one another.

1.7 The Hydrologic Cycle as Applied to Covers

An understanding of the hydrologic cycle is basic to an understanding of the functioning of a cover system. The hydrologic cycle refers to the continuous process in nature whereby water is continually in movement and transition. Summaries of this complex process can be found in numerous texts, e.g., Davis and DeWiest (1966) or Gilluly, Waters, and Woodford (1959). Those processes that take place in and about a landfill are those that require closer attention.

Elements of the hydrologic cycle important at a landfill site are shown in a simplified way in Figure 1-1. Most of these elements will be familiar to the engineer. Brief discussions of them follow.

Rainfall and snowfall, the two common forms of precipitation, need little explanation. Both are measured and reported in linear units, commonly inches in the United States. Technically the linear measurement can be thought of as the quotient of a volume of material being deposited on an area of ground. For hydrologic analysis, snowfall should be reduced to equivalent rainfall, that is, amount of water resulting from melting of a given quantity of snow.

Runoff in the context of a landfill is equivalent to surface runoff in a hydrogeological discussion (e.g., Davis and DeWiest, 1966, p. 23). It refers to that portion of the water that, having fallen on the ground, leaves the system without penetrating beneath the ground surface.

Evaporation is the process by which liquid water evaporates into gaseous water vapor, and thus passes into the atmosphere. Transpiration is the process by which plants lose water to the atmosphere. It is common to refer to evaporation and transpiration jointly as "evapotranspiration" since it is

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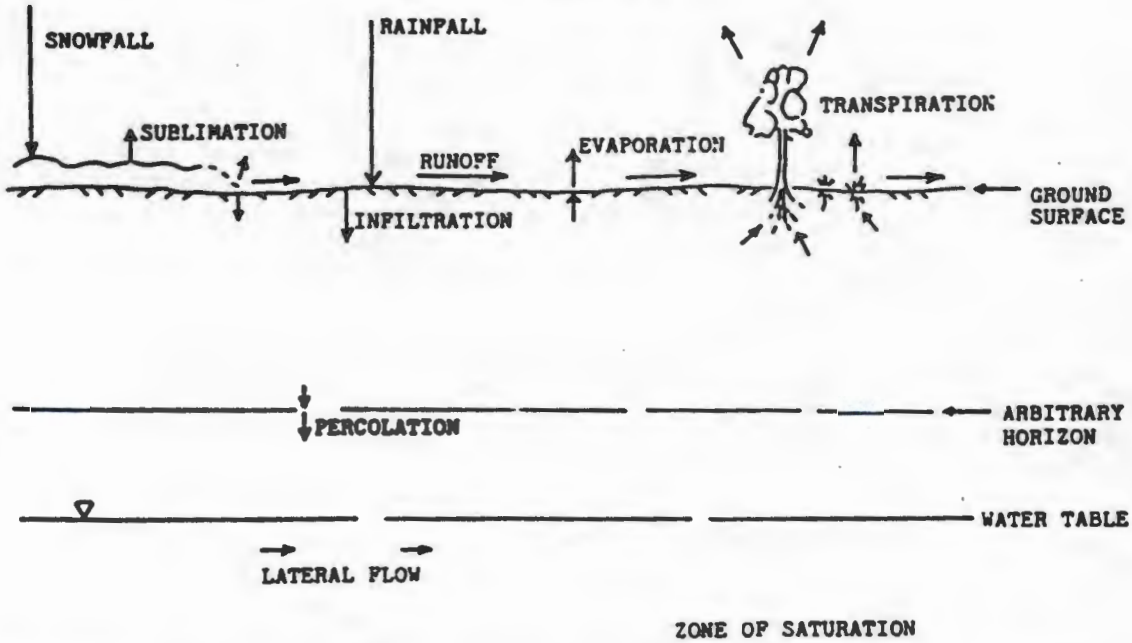
FIGURE 1-1

ELEMENTS OF HYDROLOGIC CYCLE



difficult to measure the two effects separately. Nevertheless it is probably well to remember that they are two distinct processes.

Sublimation is the direct passage of water from its solid state in snow to its gaseous state in water vapor without passing through a liquid stage. Probably a considerable amount of moisture that falls as snow returns to the atmosphere via this pathway.

Infiltration is the passage of water downward through the ground surface and into the soil.

Percolation is the downward migration of infiltrated water. As indicated in Figure 1-1, its quantity at any given horizon would be the net downward flow passing that horizon.

The water table is a level below which the ground is saturated. The zone of saturation may continue downward indefinitely, in which case the water table is a general water table; or the saturated zone may bottom at an impervious boundary of finite extent, there being further unsaturated material beneath this impervious boundary. In such cases the water is said to be perched, and the water table is a perched water table.

The water in the zone of saturation is what is commonly termed ground water, and in general it is in motion laterally as indicated in Figure 1-1.

An important factor not shown in Figure 1-1 is water storage in the soil. Depending upon its mechanical composition, a given soil can hold any given amount of water, up to a maximum. At this maximum water content, the soil is saturated. At some lesser water content, known as the field capacity, the soil holds all of its water in place, without allowing it to drain by gravity. Only in soils with more water than the field capacity does gravity drainage freely take place. The soil thus can and does act as a reservoir, which is full when the soil moisture is at field capacity. The filling and emptying of this reservoir over time plays a vital role in the local hydrologic cycle, and in the performance of a cover system. A clear, easy-to-understand discussion of this process is given in Fenn, Hanley, and De Geare (1975). (Some slight drainage may in fact occur with water contents short of field capacity, but the outline given here is basically correct.)

Those components of the hydrologic cycle that affect the functioning of a cover system are discussed in detail in section 4.2 of this Handbook, "Infiltration and Percolation."

For a proper response at any Superfund site, it is extremely important that the ground-water regime be well understood. A large proportion of the site exploration budget may properly go for this purpose. Such exploration will probably have been done as part of the early Superfund response. The cover designer should assure himself that the ground-water regime is well established, since such knowledge is essential to the proper design of cover as well as other remedial measures.

On a long-term basis the hydrologic system may be in equilibrium, i.e., operating at a steady state. However, on a short-term basis many, perhaps most, elements of the system are in other than a steady state, their positions, rates, or measurable attributes fluctuating around a steady-state average. Some fluctuations are large and rapid, others may be very slight and slow.

The more variable processes and properties tend to be those higher in the cross section - nearer to the ground surface. Those at depths vary more slowly and probably over smaller ranges. This points up a marked difference between the cover and the liner at a waste-disposal site, both of which serve to intercept and control the flow of fluids. The hydrologic processes operating in a cover system are likely only rarely to be in a steady state. Most of the time they will be varying from one state to another. In a liner, on the other hand, conditions once established will tend to persist, and a fairly close approach to steady state will exist. This has important applications for example in considering the flow of intergranular fluids. Such flow under saturated conditions and at a steady state is described by Darcy's Law, with which most engineers are familiar and which is discussed later in this Handbook. Darcy's Law as applied to liners is probably quite valid. For covers, however, it is probably only an approximation, describing what would take place under certain limiting conditions, which might occasionally occur but which probably usually do not.

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CHAPTER 2

SITE CHARACTERIZATION

This chapter discusses those characteristics of a site that affect a cover system's construction or influence its performance, and therefore must be considered in the process of cover design. A design may be seriously deficient if it fails to take into account the pertinent features and peculiarities of the site.

The designer of cover, or of other remedial measures, should have at his disposal the results of a site investigation performed earlier in the Hazardous Substance Response process (see Section 1-1). The purpose of this chapter is to serve as a check against the Site Investigation report, to determine if all pertinent characteristics were covered.

2.1 Data Requirements

The site package should include the following types of data:

- Topography
- Soils
- Geology
- Hydrology and hydrogeology
- Aerial photographs
- Cultural features
- Vegetation
- Climate
- Waste characteristics

If the site investigation report does not have adequate data to design a cover system, then the designer must rely on two types of data collection activities: (a) consult background or readily available data, and/or (b) perform an onsite investigation. The following paragraphs are devoted mainly

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to collecting available data, with only a short discussion of onsite investigation. This is not intended to imply that the latter is unimportant; indeed, specific site information is essential to proper cover design. However, a detailed presentation of investigation methods would require an extensive treatment. It was decided not to undertake such a treatment here. References are given, however, to several works that provide guidance for site investigation.

2.2 Data Sources

Sisk (1981) presents an excellent summary of the relevance and availability of background information for hazardous waste site investigations and is recommended for consultation by the cover designer. Another reference manual which is readily available and highly recommended is the U. S. Bureau of Reclamation "Earth Manual" (U. S. Bureau of Reclamation, 1974), which gives abundant information of direct interest to the cover designer for obtaining background information and also as regards all phases of soils.

Data collection activities are discussed in the following paragraphs for each type of data required.

2.2.1 Topography

The topographic map is probably the most useful single document relative to a cover project. The map reveals the lay of the land at the project site and in its vicinity; shows the surface drainage network, a matter of fundamental importance; gives information as to presence and location of cultural (man-made) features; and makes it possible to define place locations specifically by any desired system: latitude and longitude, public-land system (township, range, section, and subsection), or state coordinate system.

The U. S. Geological Survey (USGS) is the source of most published topographic maps. The scales of published topographic maps are 1:24,000 (1 in. equals 2,000 ft) or 1:31,680 (1 in. equals 1/2 mile) for 7-1/2-minute quadrangles, 1:62,500 (1 in. equals approximately 1 mile) for 15-minute quadrangles, and 1:250,000 (1 in. equals about 4 miles).* It will always be necessary to have a site topographic map at a larger scale than that of the published maps. Nevertheless the published quadrangle map should be obtained as a basic reference. An index of each state showing the available coverage and topographic quadrangle maps may be obtained direct from the USGS at addresses shown in Appendix J. In many cases selected maps are also available locally in various cities from commercial dealers. Informative discussions of topographic quadrangle maps are given in the Earth Manual (U. S. Bureau of Reclamation, 1974b), Thompson (1979), and Krynine and Judd (1957).

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* Numerical data in this Handbook are presented in units corresponding to current American usage. A metric conversion table may be found in Appendix D.

2.2.2 Soils

The U. S. Department of Agriculture has published an extensive series of soil survey maps. These maps are discussed and described in U. S. Bureau of Reclamation (1974b) and Krynine and Judd (1957), and a complete listing to date of published soil surveys is presented in an appendix to Sisk (1981). Commonly these surveys are performed on a county basis, but many are on an area basis and include portions of one or more than one counties. These surveys are performed for agricultural purposes and they are biased toward agricultural requirements. Mapped soil units are called soil series and are named for a county, city, river valley, etc., where they are typically developed. A soil series, however, reflects only the soils in the agricultural soil profile, which is usually less than 6 ft deep. Reports since 1975 contain engineering uses of soils mapped, parent materials, geologic origin, climate, physiographic setting, and soil profiles. The soil maps are presented on photomosaic background for each county at a scale of 1:15,840 or 1:20,000. Recent reports include engineering test data for soils mapped, depth to water and bedrock, grain-size distributions, engineering interpretations, and special features.

Not many soils maps have the soils classified in engineering terms. However, an instructive discussion of the geography of soils considered from an engineering point of view, with maps covering North America, may be found in Woods, Miles, and Lovell (1962). Informative discussions of the formation and distribution of soils may also be found in Peck, Hanson, and Thornburn (1974) and Mitchell (1976).

For many sites, information from nearby soil borings may be found in the files of the pertinent state highway department.

2.2.3 Geology

A variety of geological reports and maps are available for the cover designer. The scales of geologic maps include 1:24,000, 1:62,500, 1:100,000, 1:250,000, and smaller. There are two major types of geologic maps. One is the <u>formation</u> or "bedrock" geologic map, which, for a given area, indicates the material <u>underlying</u> the overburden soils. This is the most common type of geologic map; <u>state</u> geologic maps fall in this category. The other type is the <u>surficial</u> geologic map, which specifically indicates the material lying at the ground surface. Glacial-geology maps are probably the most common geologic maps in this category. Both types may be useful in locating sources of natural cover material. The principal sources of geologic maps and reports are the USGS and the State Geological Surveys or Departments of Natural Resources. See Appendix J for addresses.

A new series of indexes of geologic maps for each state was started in 1976, and lists of geological maps and reports for each state are published periodically by the USGS. Each state geological survey has a list of maps and reports published covering its state.

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Discussions of geologic maps and their use for engineering purposes are presented in Krynine and Judd (1957) and in U. S. Bureau of Reclamation (1974b).

2.2.4 Hydrology and Geohydrology

Maps showing hydrologic and hydrogeological information provide a valuable source of data in surface drainage, well locations, ground-water quality, ground-water levels, seepage patterns and aquifer locations and characteristics. A good source is the USGS which has prepared Hydrologic Investigations Atlases with a principal map scale of 1:24,000. The atlases include water availability, flood areas, surface drainage, precipitation and climate, geology, availability of ground and surface water, water quality and use, and streamflow characteristics. Some maps show ground-water contours and location of wells.

Some of the state field offices of the Water Resources Division of the USGS have water well logs which may be useful.

2.2.5 Aerial Photographs

High-quality, large-scale (1:20,000) stereoscopic aerial photographs are particularly useful for interpretating drainage patterns, topography, landforms, vegetation, land use, and cultural features. The most readily available aerial photographs are panchromatic (black and white). Other types that are available include color and color infrared, which are extremely useful but coverage is less extensive and more expensive than black-and-white air photos. The principal sources of aerial photographs are the Department of Agriculture's Agricultural Stabilization and Conservation Service (ASCS) Aerial Photography Field Office, 2511 Parley's Way, Salt Lake City, Utah 84109, and the USGS. The USGS has four mapping centers where aerial photographs may be obtained, located in Denver, CO, Rolla, MO, Menlo Park, CA, and Reston, VA. For complete addresses see Appendix J. Good discussions of the use of air photos and how to obtain them are given in U. S. Bureau of Reclamation (1974b), Sisk (1981), Krynine and Judd (1957), and Office, Chief of Engineers, Engineering Pamphlet 70-1-1.

2.2.6 Cultural Features

Cultural features that should be the concern of the cover designer include transportation, network utilities (pipelines, telephone and power lines), location of urban centers, and availability of manufactured construction materials. Some of the data listed above can be extracted from the maps previously discussed, and other data can be obtained from the local Chamber of Commerce, the city or county engineer, utility companies, and local construction contractors.

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2.2.7 Vegetation Data

Information on existing vegetation in the site vicinity is important from a cover standpoint. Vegetative protection of the cover is an important factor. Volunteer plant species in the area are an indicator of highly stable species and of species likely to invade the cover spontaneously. Cultivated plants in the area are also obviously stable locally, although requiring certain specific management practices. Sources of background information include:

- USDA - Agricultural County Agents
  - ARS - Agricultural Research Centers
- SCS - Local Offices
  - Technical Service Centers
  - Plant Materials Centers
  - Plant Materials Specialists
- U. S. Forest Service - Local or State Offices
  - Forest and Range Experiment Stations
- U. S. Army Corps of Engineers - District Offices, Environmental Resources Section
  - USAE Waterways Experiment Station, Environmental Laboratory
- County or Municipality - Land Use Planners
  - Land Use Plans
- State Universities - Local Faculty - Plant Identification

2.2.8 Climatic Data

The climatic or meteorological data for a given site is an important factor as regards cover. The cover, more than any other component of the remedial system, is directly exposed to the weather. Climate directly affects vegetation; the climatic factor of precipitation forms the input to the infiltration-percolation process that the cover system is intended to control; other climatic factors and their distribution influence the process strongly. Specific climatic data are required as input to the hydrologic modeling methods discussed later in the Handbook as means to predict a cover system's effectiveness. Weather conditions directly affect construction operations and may be important in planning the construction phase of cover installation.

Climatic data must be obtained from background sources, since a historical picture, rather than merely a short-term sampling, is important. The primary source of climatic data in the United States is the National Climatic Center (NCC), operated by the National Oceanic and Atmospheric Administration of the U. S. Department of Commerce. The NCC's address is: National Climatic Center,

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Federal Building, Asheville, NC 28801 (Telephone number: (704) 258-2850). A list of publications and publication series may be obtained from NCC by written or telephonic request. Some of these publications are listed in Table 2-1.

TABLE 2-1

SELECTED PUBLICATIONS OF THE NATIONAL CLIMATIC CENTER

Title	Publication Frequency	Contents
Local Climatological Data (LCD)	Monthly; annually	Meteorological data for 285 National Weather Service stations
Climatological Data (CD)	Monthly; annually	Meteorological data for states and combinations of states
Storm Data	Monthly	Information on severe storms
Monthly Climatic Data for the World (MCDW)	Monthly	Meteorological data for selected stations throughout world
Hourly Precipitation Data (HPD)	Monthly; annually	Hourly and daily precipitation data for states or combinations of states (except Alaska)
Climatic Atlas of the United States	--	80-page large-format collection of 231 maps, 21 graphs, and 13 tabulations depicting various aspects of climate of the U. S.
Selected Climatic Maps of the United States	--	Abbreviated version of Climatic Atlas consisting of 32 maps
Climates of the States	--	Published for each state; summary of state climate, tabulated data excerpted from pertinent annual state LCD's, climatological summary for selected locations in state. (Climatography of the U. S., No. 60)

2.2.9 Waste Characteristics

From the point of view of the remedial action as a whole, it is important to know as specifically as possible the type and form, the quantity, and the location of buried wastes. Material representing a collapsible foundation, such as buried drums of liquid, presents a threat to cover stability. Wastes that evolve gases are of concern to the cover designer; he should know if possible what will be evolved and in what quantities. In general, the cover is probably free from attack by aggressive liquids in the waste; in this respect the cover designer's problem is very much simpler than that of the designer of a liner or a slurry wall. In some topographic situations, a sloping cover might be attacked by laterally migrating liquids. In such cases the designer should be informed as to the compatibility of his cover materials with the wastes.

Source of available data on the waste site include the city or county sanitation department or the operator/owner of the site. The state EPA or its equivalent may have data on the site. A high probability exists that available

data pertaining to a Superfund site have been collected because these data were necessary to place a site on the list of Superfund sites.

2.3 Specific Site Investigations

If sufficient information is not available from background sources or from previous site investigations the designer will need to collect additional specific site data. These may include preparation of site topographic maps, programs aimed at detecting and locating buried objects, including waste containers, or explorations of the site soil profile and of available soil borrow areas in the vicinity. It is not within the scope of this Handbook to describe the investigation techniques required. Guidance is available from various sources, many of which are listed in Table 2-2.

Useful guidance for soil exploration may be found in the highway plan of the state highway department. This plan is oriented toward the geology of the particular state and the specific exploration methods found necessary there.

TABLE 2-2

SOURCES OF GUIDANCE FOR SITE INVESTIGATIONS

Soils Exploration
American Society for Testing and Materials (annual, Part 19; specifically, D-420)
Clayton, Simons, and Matthews (1982)
Department of the Army (1984)
Hough (1969)
Hvorslev (1948)
Krynine and Judd (1957)
Parcher and Means (1968)
Peck, Hanson, and Thornburn (1974)
Sowers and Sowers (1970)
Taylor (1948)
Teng (1962)
Terzaghi and Peck (1967)
Tomlinson (1969)
U. S. Bureau of Reclamation (1974a; 1974b)
Geophysical Methods
Clayton, Simons, and Matthews (1982)
Department of the Army (1979, 1984)
Dobrin (1976)
Evans (1982)
Telford et al. (1976)

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CHAPTER 3

MATERIALS USED IN COVER SYSTEMS

3.1 Introduction

The overriding purpose of a cover system is to hinder water from entering the wastes from the top. The attributes of the cover must include stability against erosion, slumping and cracking, slope failures, disruption by animals and plants, and disruption by the effects of cold or hot, dry weather. The ideal cover would perform as a tight roof and possess all these attributes. In reality, these goals may work against one another, and any or all of them may work against the goal of minimum cost. The task of the designer is to achieve the best balance among competing goals at an acceptable cost.

This chapter deals with materials that the cover designer has at his disposal. The following chapter deals with the process of design itself - how the materials are combined and put to use. A designer may be guided by his own experience or knowledge of successful measures used elsewhere. The one indispensable requirement for any material is that it must do the job at hand.

In this Handbook, materials have been divided into two basic categories, soils and nonsoils, following the practice of Lutton, Regan, and Jones (1979). Soils may be defined for present purposes as any naturally occurring particulate material. Discussed under soils are various mineral-based additives by which soil properties may be amended. Their use results in what are known as stabilized or modified soils. Nonsoils include a variety of materials and supplies, some synthetic and some natural. Living matter such as vegetation is not considered under "materials."

The discussion of soils and their properties which follows is somewhat broader than necessary for a design manual. This approach has been adopted in an effort to provide technical background for the benefit of regulatory personnel without geotechnical training.

3.2 Soils as Cover Materials

Soils will form the great majority of the materials used in any cover system. This section deals with the attributes of soils that lead to their classification and their functioning in cover applications.

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3.2.1 General Soil Factors

Simple definitions of soil are relatively easy, but an all-comprehensive one is difficult. A definition of soil in the literature of any specialty tends to stress the attributes of interest to that specialty and to slight those of interest to others. Certainly the most basic attribute of soil is that it is a particulate material. In general soil is a natural material, and any particulate material produced by human activities is to be regarded separately. The agronomist is concerned with soil as a medium to sustain plant life, and stresses the organic content of soil as an essential part of its definition. This characteristic may be of little or no interest to the engineer or geologist. The engineer is concerned with the mechanical properties of a soil and its behavior as an engineering material. Very often these are directly related to the presence and action of water. Both water and organic matter are mobile, variable components of a soil.

The cover designer is predominantly concerned with soils from the viewpoint of the engineer. However, he shares the concern of the agronomist, because he is interested in producing a cover with stable vegetation. Most of the discussion of soils in this Handbook will be engineering-oriented, but factors important to vegetation will be outlined also.

One characteristic of any particulate aggregation is its gradation. Mechanical analysis, mechanical composition, and particle-size distribution are all synonymous terms for gradation. This basic characteristic is a component in all the soil-classification systems discussed below.

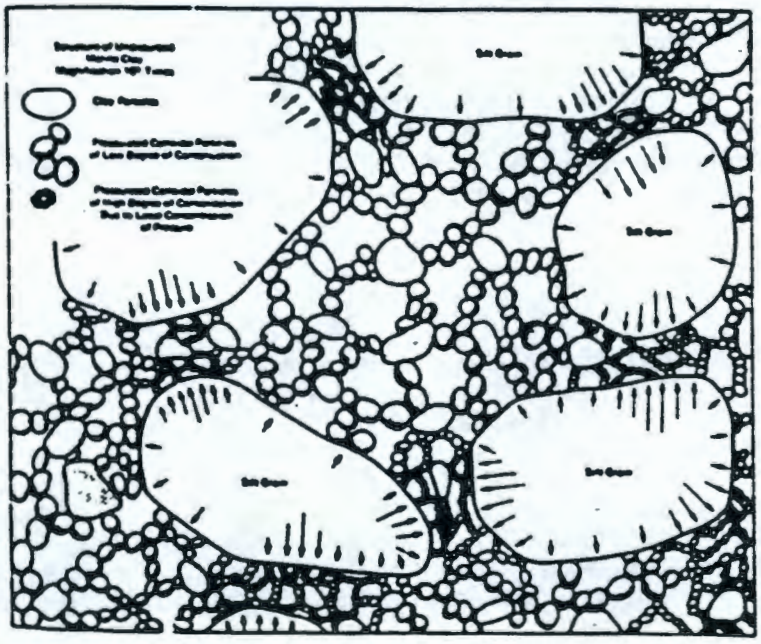
Because soil is a natural material, its grains or particles are composed of mineral (or organic) substances. The most common mineral in the coarse grains is quartz (crystalline silicon dioxide, SiO_2). This mineral is a hard, stable mineral lacking in cleavage, and thus forming equant grains without flat or long shapes. By contrast, a variety of minerals form the fine grains. These include quartz, oxide minerals such as aluminum and iron oxides, and organic matter; but the dominant and most important component is the large and complex group known as the "clay minerals." These are silicate minerals with a distinctly planar structure (phyllosilicates), in contrast to quartz. Because of their small size and platy shape, the specific surface of fine-grained soils, and particularly those rich in clay minerals, is enormously greater than that of coarser-grained soils.

Any particulate aggregation is characterized by the factors of structure and texture. These related terms refer to the arrangement or disposition of individual grains relative to one another. For the relatively simple shapes of grains in the coarse fraction this refers to looseness or denseness of packing. For the more complexly shaped grains of the fine fraction, this includes both packing and such effects as flocculent structure (Figure 3-1).

The particulate skeleton of a soil may be regarded as its "permanent" part. The void space between the particles is filled with air, water, or both. These fluid components play an exceedingly important part in determining soil properties and behavior, especially in the fine-grained soils.

FIGURE 3-1

FLOCCULENT STRUCTURE OF SENSITIVE CLAY SUGGESTED BY A. CASAGRANDE (1932)



Both the quantity of water and its disposition with regard to soil particles and mineral molecules play important behavioral roles, from both engineering and agricultural standpoints.

Discussions of the complex clay-water-electrolyte system that exists in a fine-grained soil may be found in various articles and texts, e.g., Mitchell (1976). Clay-mineral molecules*, because of widespread substitution among the ions forming their crystal structure (Si^{++++}, Al^{+++}, Ca^{++}, Mg^{++}, and others), routinely have net residual electrical charges. They thus attract to their surfaces ions in solution as well as the appropriate ends of water molecules. (The water molecule is "polar," i.e., electrically asymmetrical.) The phenomenon is known as adsorption (see definition in glossary). The adsorptive forces are of varying strengths, and a wide variety of surface-related electrochemical phenomena are possible and indeed take place.

Besides minerals and fluids, some soils have one or more organic components. Most agricultural soils are basically mineral soils in which organic matter has become incorporated through plant and animal growth. There are also soils whose basic components are organic matter, such as peats.

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* "Molecule" is used here in a general sense; it is recognized that ionic substances, such as most minerals, may not contain discrete molecules as such.

To geographers and geologists, the origin of a soil is of importance. The two major subdivisions by origin are residual and transported soils. The residual soils are simply the altered part of rock which has decomposed. The transported soils represent particulate material that was once a residual soil but has been eroded, transported, and deposited as a sediment. Various sedimentary processes lead to different types of soil deposits. Such terms as "glacial" or "alluvial" soils refer to mode of origin. Origin is not a descriptive matter, but requires inference from a study of various factors. Knowledge of a soil's origin is not essential when using it in an engineering application, but such knowledge can often be very helpful in interpreting, understanding, and even predicting observable descriptive factors.

3.2.2 Common Soil Terms

Certain basic soil descriptive terms need to be understood. Gravel comprises granular material of coarse to very coarse grain size. The grains in sand range from coarse down to fine but still visible with the naked eye. Silt is the coarser and less plastic portion of the material finer than sand. Clay is the finer and more plastic portion of the material finer than sand. The term "fines" applies collectively to silt and clay. Loam is a term used only in agricultural classifications and designates a mixture comprising sand, silt, and clay, or at least two of these three components. The numerical limits of these size fractions are discussed below under "classification."

The term "clay" is sometimes misunderstood because it is used in three related yet distinct senses. "Clay sizes" refers to particles less than 2 microns in dimension (0.002 mm) (or other limiting size, depending on system in use). "Clay" used alone refers to a natural material that behaves plastically when wet, within a certain range of moisture content. The "clay minerals" refer to a distinct group of mineral species, all of which are hydrous aluminosilicates with a platy crystal structure. The most common clay minerals are kaolinite, montmorillonite, illite or hydrous mica, and chlorite. Confusion arises because a soil may be composed of clay-sized particles of minerals other than the clay minerals (e.g., quartz, other forms of silica, oxides of iron or aluminum). Such a soil is likely not to show "clay-like" (plastic) behavior.

Classification systems (see below) commonly group soils first into coarse-grained and fine-grained soils. Terms commonly associated with coarse soils are "granular" and "cohesionless." Terms commonly associated with fine soils are "cohesive" and "plastic." Within the fine-grained soils, however, there are great variations in cohesiveness and plasticity.

"Grading" refers to a soil's gradation or mechanical composition. Well-graded soils possess significant quantities of all grain sizes from coarse to fine. Poorly graded soils may be uniform, possessing only a small range of grain sizes, or "gap graded," possessing coarse and fine grains but few or none of intermediate sizes.

The terms "intact" and "remolded" refer to whether a soil is in its natural, undisturbed state or has been moved, handled, processed, or otherwise disturbed by human activity. The behavior of some soils differs drastically between the intact and the remolded states. Such considerations are important when soils serve as foundations, but are less so when the soils serve as materials, since in materials applications soils are always remolded to some degree.

3.2.3 Soil Properties

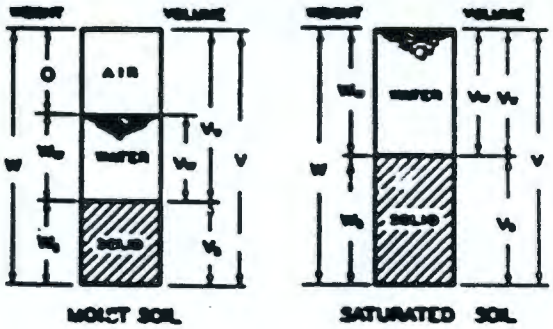
The following discussion follows Taylor (1948). A soil mass is commonly considered to consist of a network or skeleton of solid particles, enclosing voids or interspaces of varying size. The voids may be filled with air, with water, or partly with air and partly with water.

The total volume of a given soil sample is designated by V and consists of two essential parts, the volume of solids V_s and the volume of voids V_v. The volume of voids in turn is subdivided into water volume V_w and gas volume V_g. These volumes are indicated in Figure 3-2. This figure is a diagrammatic representation because all void and solid volumes cannot be segregated as shown. However, for studying interrelationships of the terms given in this section such sketches help greatly.

Volume ratios which are used in soil mechanics are porosity, void ratio, and degree of saturation.

FIGURE 3-2

DIAGRAMMATIC REPRESENTATION OF SOIL AS A THREE-PHASE SYSTEM, SHOWING WEIGHT AND VOLUME NOTATIONS AND RELATIONSHIPS



The porosity n of the soil mass is defined as the ratio of volume of the voids to the total volume of the mass.

The void ratio e of the mass is defined as the ratio of volume of voids to volume of solid.

The degree of saturation S is defined as the ratio of volume of water to volume of voids.

These ratios may be written

$$n = \frac{V_v}{V} \tag{3.1}$$

$$e = \frac{V_v}{V_s} \tag{3.2}$$

$$S = \frac{V_w}{V_v} \tag{3.3}$$

The void ratio is usually expressed as a ratio, whereas porosity and degree of saturation are commonly expressed as percentages. A variety of working relationships among these basic soil properties may be derived by simple algebraic manipulation. See, for example, Department of the Navy (1982).

Porosity as defined above is used in many branches of engineering and is more familiar than the void ratio to engineers in general. However, in soil mechanics it is more convenient in the majority of cases to use the void ratio, principally because, when a given specimen of soil is compressed, the denominator of the void ratio expression remains constant, whereas both numerator and denominator of the porosity expression vary.

The total weight of a soil sample is designated by W, the weight of solids by W_s, and the weight of water by W_w. A ratio of weights is the water content (or moisture content).

The water content w of a soil sample is defined in soil mechanics as the ratio of weight of water to weight of solids. It is commonly expressed as a percentage and may be written

$$w = \frac{W_w}{W_s} \tag{3.4}$$

The water content defined in equation 3.4 is a ratio, or percentage, of the weight of water to the weight of solids. This practice is not standard in all branches of science, the water content being defined in geology, for example, as a percentage of total weight. Therefore this definition as given

should be carefully noted. Note also that the upper limit of water content is indefinite. Some soils have water contents of several hundred percent.

The idealized concept used herein assumes that solid grains and water are two definite and separate phases of a soil. However, the actual situation is much more complex, because water may exist in a number of forms and mineral grains contain combined water. When a sample is heated to evaporate the pore water, certain amounts of combined water may also be driven off, the amount of loss of combined water depending mainly on the temperature used. To give a fixed definition of what is to be considered as water, it is commonly stated that all weight lost in evaporation by heating to 105° or 110°C is water; all remaining, solids. In other ways the simple two-phase concept is not strictly true. Dissolved salts in the water may change the unit weight appreciably; for example, sea water has a unit weight of about 1.025 grams per cc. If the sample is heated to drive off the water, the salts remain and become part of the solid weight. Therefore the diagram of Figure 3-2 must be recognized as one based on simplified concepts.

Variations in the water content of a given soil change its characteristics to such a marked degree that the importance of this soil property cannot be overemphasized.

The unit weight or weight per unit of volume is designated by γ. The following expressions hold for the mass unit weight or unit weight of the soil mass as a whole, γ_t, the unit weight of solids, γ_s, and the unit weight of water γ_w:

$$\gamma_t = \frac{W}{V} \tag{3.5}$$

$$\gamma_s = \frac{W_s}{V_s} \tag{3.6}$$

$$\gamma_w = \frac{W_w}{V_w} \tag{3.7}$$

The dry unit weight of a soil, frequently referred to as dry density, is

$$\gamma_d = \frac{W_s}{V} \tag{3.8}$$

The dry density of a soil is directly related to its void ratio. A given soil may contain varying amounts of water from none up to complete saturation, but so long as its void ratio remains constant, so does its dry density.

The specific gravity of soil solids, defined identically with other materials as a ratio of densities with respect to pure water, is relatively unimportant as regards a soil's behavior. When testing soils, it usually must be determined, however, as its value is required to compute properties such as void ratio and degree of saturation. Specific gravity is denoted G_s or simply G.

Density of soils is frequently spoken of but in an inexact way. Contrasts are drawn between "dense" or "very dense" soils and "loose" or "very loose" soils, the void ratios of the former being relatively small and of the latter being relatively large. A quantitative measure of density used for cohesionless soils is <u>relative density</u>, denoted D_d, and defined by

$$D_d = \frac{e_{max} - e}{e_{max} - e_{min}} \tag{3.9}$$

where the various e's refer to the actual void ratio and the highest and lowest possible values that soil could attain under certain specified compaction procedures. Relative density is used only in connection with granular (cohesionless) soils. Correlations exist between relative density and the commonly used Standard Penetration Test for field studies (ASTM D-1586).

3.2.4 Soil Classification

Classifications attempt to render order out of chaos by setting up a finite number of "pigeonholes" into which any individual can be placed. When a single pigeonhole is assigned, and thus all others are rejected, a good deal of information about the individual is conveyed. Soils being very complex, have been the subject of numerous classifications. The "pigeonholes" used consist of names, letter-number designations, or combinations of both.

As with definitions, classifications and even identification of soils are colored by the interest of the specialist involved. A very instructive discussion of the problem of classifying soils appears in Casagrande (1948). Two-thirds of this article consists of discussions by other specialists of the classification system designed by Casagrande which later became known as the Unified Soil Classification System (USCS). The USCS is widely used by foundation engineers in North America and is the one emphasized in this Handbook. The other two systems mentioned are the textural classification of the U. S. Department of Agriculture and the AASHTO system, commonly used by highway engineers. Reviews of these three systems are found in Peck, Hanson, and Thornburn (1974), and in the Asphalt Institute Soils Manual (1978). Gradation is a basic factor in all engineering soil-classification systems. Figure 3-3 shows the particle size limits that have been assigned to the fractions of gravel, sand, silt, and clay by various classification systems.

FIGURE 3-3

PARTICLE SIZE LIMITS OF SOIL FRACTIONS ACCORDING TO SEVERAL CLASSIFICATION SYSTEMS

Classification System	Grain Size, mm						
	100	10	1	0.1	0.01	0.001	0.0001
Bureau of Soils, 1890-95	Gravel		Sand		Silt	Clay	
			1	0.05	0.005		
Atterberg, 1905	Gravel		Coarse sand	Fine sand	Silt	Clay	
			2	0.2	0.02	0.002	
MIT, 1931	Gravel		Sand		Silt	Clay	
			2	0.06	0.002		
U.S. Dept. Agr., 1938	Gravel		Sand		Silt	Clay	
			2	0.05	0.002		
AASHO, 1970	Gravel		Sand		Silt	Clay / Colloids	
	75		2	0.075	0.002	0.001	
Unified 1953 ASTM, 1967	Gravel		Sand		Fines (silt & clay)		
	75	4.75		0.075			

(from Peck, Hanson, and Thornburn, 1974; courtesy John Wiley & Sons, Inc.)

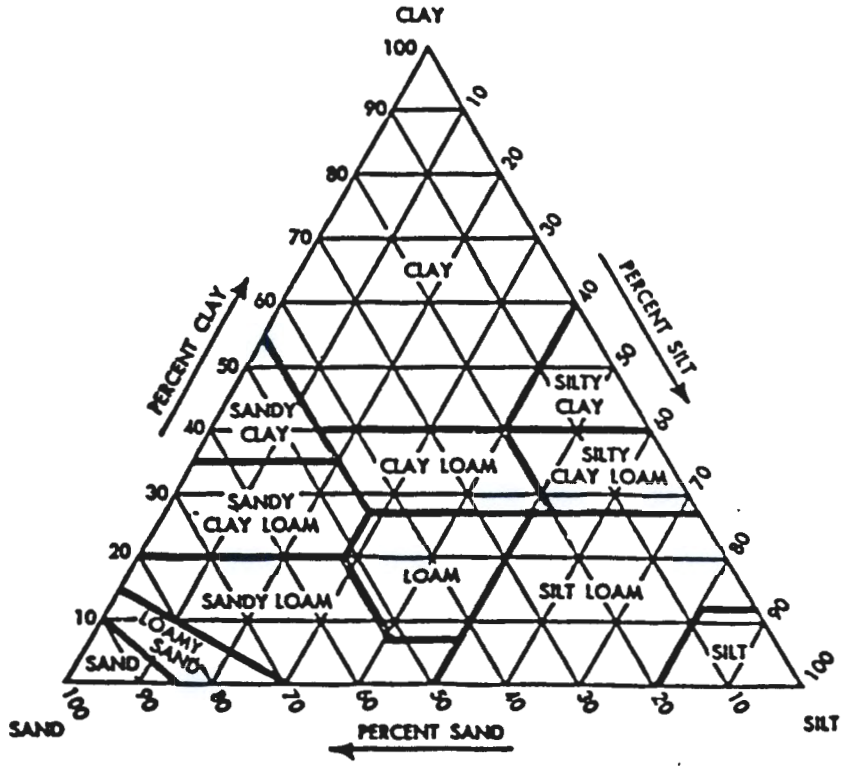
3.2.4.1 Agricultural Classification

Soil classification as practiced in agricultural soil science tends to follow a taxonomic approach, into orders, families, etc., which are not of interest to the cover designer, but which is the system used in soil survey reports. For naming of soils according to their mechanical composition, the U. S. Department of Agriculture uses a triangular chart whose vertices represent the extremes of sand, silt, and clay (Figure 3-4). Particles larger than 2 mm in dimension are excluded; if a significant amount of such coarser material is present, an adjective, "gravelly" or "stony," is applied to the soil name. The triangle is divided into fields with different soil names. From the mechanical analysis of the minus-2-mm portion of the soil the sand, silt, and clay fractions (which must add up to 100 pct) are computed. These fractions correspond to some point in the triangle. The soil is then named from the field in which the point lies.

9 3 1 2 9 0 4 0 9 4 4

FIGURE 3-4

GUIDE FOR TEXTURAL CLASSIFICATION OF SOIL USED BY U. S. DEPARTMENT OF AGRICULTURE



3.2.4.2 Unified Soil Classification System

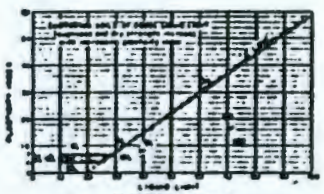
The "Unified" soil classification system (USCS) is essentially the same as the one developed during World War II by Professor A. Casagrande of Harvard University for use by the U. S. Army in designing and building military airfields, and published by Casagrande (1948) as the "Airfield Classification" system. It was subsequently adopted with minor modifications by the Corps of Engineers and the U. S. Bureau of Reclamation, and in 1969 it was adopted by the American Society for Testing and Materials as a standard method, ASTM D-2487.

The USCS has two major divisions, the coarse-grained and the fine-grained soils, and one minor division, the highly organic soils. The coarse-grained soils are further subdivided mainly on the basis of their gradation; the fine-grained soils are subdivided on the basis of their plasticity characteristics as indicated by Atterberg limits (see next section). The structure of the USCS is shown in Figure 3-5. An important element is the Plasticity

9 3 1 2 9 0 4 0 9 4 6

UNIFIED SOIL CLASSIFICATION
INCLUDING IDENTIFICATION AND DESCRIPTION

FIELD IDENTIFICATION PROCEDURES (Excluding particles larger than 3 inches and basing fractions on estimated weights)				GROUP SYMBOLS	TYPICAL NAMES	INFORMATION REQUIRED FOR DESCRIBING SOILS	LABORATORY CLASSIFICATION CRITERIA
COARSE GRAINED SOILS (More than half of material is larger than No. 200 sieve size)	GRAVELS (More than half of coarse fraction is larger than No. 4 sieve size)	Clean Gravels (Little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes	GW	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; max size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics Example: Silty sand, gravelly; about 20% hard, angular gravel particles 1/2 in. maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM)	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting all gradation requirements for GW
		Dirty Gravels (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)	GM	Silty gravels, poorly graded gravel-sand-silt mixtures		Atterberg limits below "A" line, or PI less than 4
			Plastic fines (for identification procedures see CL below)	GC	Clayey gravels, poorly graded gravel-sand-clay mixtures		Atterberg limits above "A" line with PI greater than 7
	SANDS (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean Sands (Little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes	SW	Well graded sands, gravelly sands, little or no fines		$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between one and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing	SP	Poorly graded sands, gravelly sands, little or no fines		Not meeting all gradation requirements for SW
		Dirty Sands (Appreciable amount of fines)	Non-plastic fines (for identification procedures see ML below)	SM	Silty sands, poorly graded sand-silt mixtures		Atterberg limits below "A" line or PI less than 4
			Plastic fines (for identification procedures see CL below)	SC	Clayey sands, poorly graded sand-clay mixtures		Atterberg limits above "A" line with PI greater than 7
FINE GRAINED SOILS (More than half of material is smaller than No. 200 sieve size)	IDENTIFICATION PROCEDURES ON FRACTION SMALLER THAN NO. 40 SIEVE SIZE						
		Dry Strength (crushing characteristics)	Dry Stickiness (Adhesion to fingers)	Toughness (consistency near plastic limit)			
	SILTS AND CLAYS (Liquid limit less than 50)	None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; color in wet condition; odor if any; local or geologic name, and other pertinent descriptive information, and symbol in parentheses For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions Example: Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML)	See Plasticity Chart below for laboratory classification of fine grained soils
		Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	
		Slight to medium	Slow	Slight	OL	Organic silts and organic silt-clays of low plasticity	
	SILTS AND CLAYS (Liquid limit greater than 50)	Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	
		High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays	
		Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity	
HIGHLY ORGANIC SOILS		Readily identified by color, odor, spongy feel and frequently by fibrous texture			Pt	Peat and other highly organic soils	



1 Boundary characteristics: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well graded gravel sand mixture with clay binder.

2 All sieve sizes on this chart are U.S. standard.

FIELD IDENTIFICATION PROCEDURES FOR FINE GRAINED SOILS OR FRACTIONS

These procedures are to be performed on the minus No. 40 sieve size particles, approximately 1/64 in. For field classification purposes, screening is not intended; simply remove by hand the coarse particles that interfere with the tests.

DILATANCY (Reaction to shaking)

After removing particles larger than the No. 40 sieve size, prepare a pat of moist soil with a volume of about one-half cubic inch. Add enough water if necessary to make the soil soft but not sticky.

Place the pat in the open palm of one hand and shake horizontally, striking vigorously against the other hand several times. A positive reaction consists of the appearance of water on the surface of the pat which changes to a livery consistency and becomes glossy. When the sample is squeezed between the fingers, the water and gloss disappear from the surface, the pat stiffens, and finally it cracks or crumbles. The rapidity of appearance of water during shaking and of its disappearance during squeezing assist in identifying the character of the fines in a soil.

Very fine clean sands give the quickest and most distinct reaction whereas a plastic clay has no reaction. Inorganic silts, such as a typical rock flour, show a moderately quick reaction.

DRY STRENGTH (Crushing characteristics)

After removing particles larger than the No. 40 sieve size, mold a pat of soil to the consistency of putty, adding water if necessary. Allow the pat to dry completely by oven, sun, or air drying, and then test its strength by breaking and crumbling between the fingers. This strength is a measure of the character and quantity of the colloidal fraction contained in the soil. The dry strength increases with increasing plasticity.

High dry strength is characteristic for clays of the CH group. A typical inorganic silt possesses only very slight dry strength. Silty fine sands and silts have about the same slight dry strength, but can be distinguished by the feel when pulverizing the dried specimen. Fine sand feels gritty whereas a typical silt has the smooth feel of flour.

TOUGHNESS (Consistency near plastic limit)

After removing particles larger than the No. 40 sieve size, a specimen of soil about one-half inch cube in size is molded to the consistency of putty. If too dry, water must be added and if sticky, the specimen should be spread out in a thin layer and allowed to lose some moisture by evaporation. Then the specimen is rolled out by hand on a smooth surface or between the palms into a thread about one eighth inch in diameter. The thread is then folded and rerolled repeatedly. During this manipulation the moisture content is gradually reduced and the specimen stiffens, finally loses its plasticity, and crumbles when the plastic limit is reached.

After the thread crumbles, the pieces should be lumped together and a slight kneading action continued until the lump crumbles.

The tougher the thread near the plastic limit and the stiffer the lump when it finally crumbles, the more potent is the colloidal clay fraction in the soil. Weakness of the thread at the plastic limit and quick loss of coherence of the lump below the plastic limit indicate either inorganic clay of low plasticity, or materials such as kaolin-type clays and organic clays which occur below the A-line.

Highly organic clays have a very weak and spongy feel at the plastic limit.

FIGURE 3-5

THE UNIFIED SOIL CLASSIFICATION SYSTEM

Chart, in the lower right, which is used in the identification process once the liquid and plastic limits have been determined. The "A" line on this chart marks an empirical boundary identified by Casagrande (1948) between inorganic and organic plastic clays and between inorganic clays and inorganic silts. It is defined by the equation: PI = 0.73 (LL - 20). Note also the three simple field tests at the bottom of the chart, used for quick identification of fine-grained soils.

The USCS classifies soils into Groups, each designated by a two capital letter symbol. The letters are symbols pertinent to constituents or attributes of the group. Thus the following letter associations: G, gravel; S, sand; M, silt; C, clay; Pt, peat; O, organic; W, well (graded); P, poorly (graded); H, high (liquid limit); L, low (liquid limit). Note the mnemonic significance of most of the symbols. Thus for instance GW is well-graded gravel, SM is silty sand, and CH is clay (inorganic) of high liquid limit.

An approximate correlation can be made between the USDA and the Unified systems. In Figure 3-6, USCS symbols have been superimposed on the triangular textural chart, and in Table 3-1 corresponding designations in the two systems are listed. The reader should note that these are the usual correlations between USDA and USCS systems. However, other combinations are possible. A careful study of Figure 3-6 and Table 3-1 will show several cases of overlaps, ambiguities, and missing groups; therefore, conversions can be only approximate. The importance of the USCS from an engineering point of view is further discussed below.

Descriptions of specific procedures for classifying a soil according to the USCS are given in the following manuals and designations: ASTM, D-2487; USBR, E-3; USCE, WES Technical Memorandum 3-357 (Geotechnical Laboratory, 1982).

3.2.4.3 AASHTO Classification

A third classification system in common use among highway engineers is known as the AASHTO (American Association of State Highway and Transportation Officials) (formerly AASHO) system. Soils are grouped into seven classes, in approximate order of quality as a highway subgrade (basement) material. Groups A-1 through A-3 comprise granular soils, groups A-4 through A-7 comprise silt-clay materials. An eighth group comprises organic soils. The system is primarily based on mechanical analysis, but plasticity enters into the classification of the silt-clay groups. The system is presented in the AASHTO Specifications volume (AASHTO Designation M-145) and discussed in the Asphalt Institute Soils Manual as well as in texts on highway engineering and foundation engineering. Its structure is shown in Table 3-2.

3.2.5 Soil Tests

To determine a soil property, it is usually necessary to perform one or more tests. Very little can be determined simply by visual observation. The

9 3 1 2 9 0 4 0 9 4 7

FIGURE 3-6

COMPARISON OF USCS AND USDA SOIL TERMINOLOGY
(FROM MEYER AND KNIGHT, 1961)

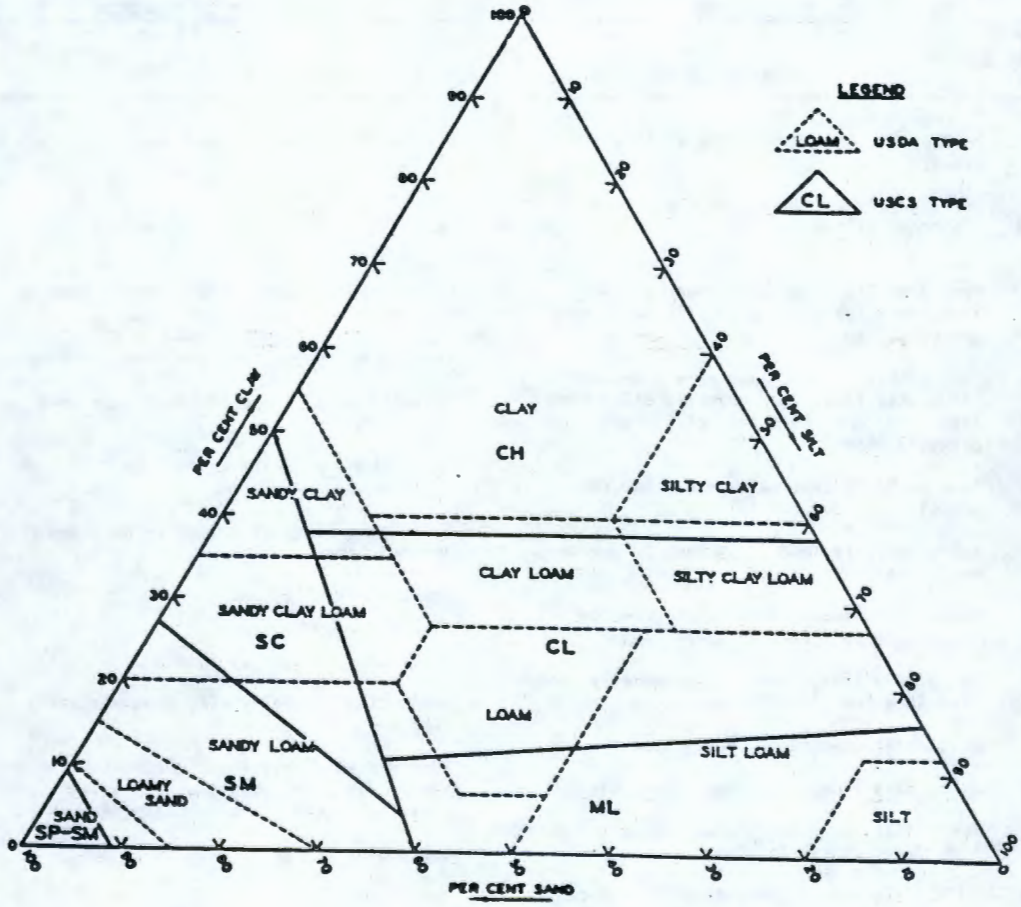


TABLE 3-1

USUAL CORRESPONDENCE BETWEEN USCS AND USDA SOIL DESIGNATIONS

(A) USDA TEXTURAL TYPES CORRESPONDING TO USCS SOIL DESIGNATIONS

USCS Soil Type	USDA Soil Types
GW	Same as GP (except well graded in grain sizes)
GP	Gravel, very gravelly sand (less than 5 percent silt and clay)
GM	Very gravelly sandy loam, very gravelly loamy sand, very gravelly silt loam, very gravelly loam
GC	Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay, very gravelly clay
SW	Same as SP (except well graded in grain sizes)
SP	Sand, gravelly sand (less than 20 percent very fine sand)
SM	Loamy sand, sandy loam; sand; gravelly loamy sand and gravelly sandy loam
SC	Sandy clay loam, sandy clay; gravelly sandy clay loam and gravelly sandy clay
ML	Silt, silt loam, loam, sandy loam
CL	Silty clay loam, clay loam, sandy clay
OL	Mucky silt loam, mucky loam, mucky silty clay loam, mucky clay loam
MH	Silt, silt loam (highly elastic, micaceous or diatomaceous)
CH	Silty clay, clay
OH	Mucky silty clay
PT	Muck, peat

(B) USCS SOIL TYPES CORRESPONDING TO USDA SOIL TERMINOLOGY

USDA Soil Type	USCS Soil Type
Gravel, very gravelly loam sand	GP, GW, GM
Sand	SP, SW
Loamy gravel, very gravelly sandy loam, very gravelly loam	GM
Loamy sand, gravelly loamy sand, sand	SM
Gravelly loam, gravelly sandy clay loam	GM, GC
Sandy loam, gravelly sandy loam	SM
Silt loam, sandy clay loam (with fine-grained sand)	ML
Loam, sandy clay loam	ML, SC
Silty clay loam, clay loam	CL
Sandy clay, gravelly clay loam, gravelly clay	SC, GC
Very gravelly clay loam, very gravelly sandy clay loam, very gravelly silty clay loam, very gravelly silty clay	GC
Silty clay, clay	CH
Muck, peat	PT

Note: Modified from Schomaker and Murdock (1969)

TABLE 3-2

AASHTO CLASSIFICATION OF SOILS AND SOIL-AGGREGATE MIXTURES

General Classification	Granular Materials (35% or less passing 0.075 mm)							Silt-Clay Materials (More than 35% passing 0.075 mm)			
Group Classification	A-1 A-1-a	A-1-b	A-3	A-2-4	A-2 A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7 A-7-5 A-7-6
Sieve Analysis, Percent Passing											
2.00 mm (No. 10)	50 max	--	--	--	--	--	--	--	--	--	--
0.425 mm (No. 40)	30 max	50 max	51 max	--	--	--	--	--	--	--	--
0.075 mm (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of Fraction Passing 0.425 mm (No. 40)											
Liquid Limit	--		--	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual Types of Significant Constituent Materials	Stone Fragments Gravel and Sand		Fine Sand		Silty or Clayey Gravel and Sand			Silty Soils		Clayey Soils	
General Rating as Subgrade	Excellent to Good							Fair to Poor			

Plasticity Index of A-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of A-7-6 subgroup is greater than LL minus 30 (see AASHTO Plasticity Chart).

test may be a simple qualitative one or it may be very complicated. Properties and tests will be discussed jointly in this section.

The ultimate purpose of engineering soil tests is construction. A key distinction needs to be drawn between design tests and construction tests. Design tests are performed to characterize the soil and to determine what performance may be expected from it under various conditions. Characteristically design tests are conducted in a laboratory, although some important tests are performed in the field. The project design is based on the results of the design tests, and is expressed in the project plans and specifications. Construction tests, or control tests, are performed as the project is built, and are in fact acceptance or proof tests, whose purpose is to assure that the specifications are being met. Construction tests need to be simple, rapid, and adapted to field use. A comprehensive review of all tests, both design and construction, is given by Spigolon and Kelley (1983).

The tests discussed in this section are design tests and are listed in Table 3-3. Construction tests are presented later in this Handbook.

3.2.5.1 Gradation

The gradation (mechanical analysis; particle or grain size distribution) of soils is determined by two complementary techniques, sieving for the coarser particles and hydrometer analysis for the finer ones. Sieving is a direct technique in which the soil is shaken through a nest of graded sieves, and the fraction collected on each sieve is weighed. In the United States, sieve numbers are based on the number of meshes, or wires, per linear inch. Information on sieve specifications is given in ASTM designation E-11. The relation between particle sizes and numbered sieves is shown in Figure 3-7.

Because it is not practical to sieve fine particles, the hydrometer analysis, an indirect technique, is used to determine the gradation of particles finer than the No. 200 sieve. This technique is based on Stokes' Law for the settling velocity of spheres in a viscous fluid. The method is explained in Taylor (1948) and other books on soil mechanics.

The results of a mechanical analysis are commonly plotted on a semilogarithmic plot such as Figure 3-7. The abscissa is grain size, and the ordinate is a cumulative weight percent finer than, or "passing," a given size. The amount within any given size range may be simply determined by finding the abscissa points corresponding to the boundaries of that range, reading the ordinates of the curve for those two values, and subtracting the ordinate values.

A soil with a continuous range of particle sizes is called "well graded" and is represented by a smooth grain-size curve with appreciable slope. A soil whose grains fall within a narrow size range is termed "poorly graded" and is characterized by a steep grain-size curve. A soil with appreciable coarse and appreciable fine grains but lacking in intermediate ones is termed "gap-graded" or "skip-graded" and is characterized by a "steplike" grain-size curve.

TABLE 3-3

MANUAL DESIGNATIONS OF SELECTED ENGINEERING SOIL TESTS

Test	ASTM	AASHTO	USBR	USCE
Gradation (Mechanical Analysis)	D-422[a]	T-88	E-6	Appendix V
Water Content	D-2216	--	E-9	Appendix I
Specific Gravity	D-854	T-100	E-10	Appendix IV
Liquid Limit	D-423	T-89	E-7	Appendix III
Plastic Limit	D-424	T-90	E-7	Appendix III
Shrinkage Limit	D-427	T-92	E-7	Appendix III
Relative Density	D-2049	--	E-12	Appendix XII
Standard Proctor Compaction	D-698	T-99	E-11	Appendix VI
Modified Proctor Compaction	D-1557	T-180	--	Appendix VI
One-Dimensional Consolidation	D-2435	T-216	E-15	Appendix VIII
Strength Tests		[b]		
Permeability	--	See Table 3-4		
Shrink/Swell Behavior	D-3877	--	--	Appendix VIII-A

[a]Other specialized ASTM designations relate to gradation.

[b]There are many different strength tests with varying special applications. Certain strength tests yield the Modulus of Elasticity from which the flexibility of the cover can be evaluated. For strength tests consult the referenced manuals.

Manuals referred to in this table are the following:

ASTM: "Part 19: Soil and Rock; Building Stones" of the "Annual Book of ASTM Standards," published annually by the American Society for Testing and Materials, Philadelphia, PA.

AASHTO: "Standard Specifications for Transportation Materials and Methods of Sampling and Testing," published every four years by the American Association of State Highway and Transportation Officials, Washington, DC.

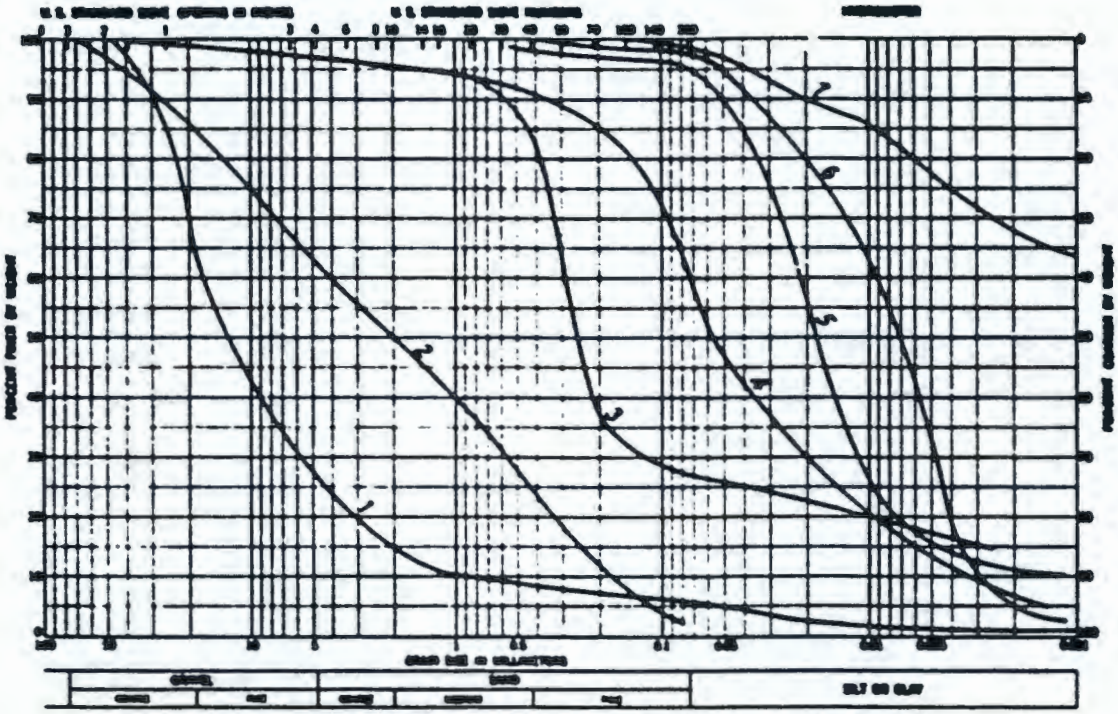
USBR: "Earth Manual," 2nd edition (1974), published by the Bureau of Reclamation, U. S. Department of the Interior.

USCE: "Laboratory Soils Testing," Engineer Manual EM 1110-2-1906 (1970; revision issued 1980), published by the Office of the Chief of Engineers, U. S. Department of the Army.

9 3 1 2 9 0 4 0 9 5 2

FIGURE 3-7

GRADATION CURVES OF SOME SANITARY-LANDFILL COVER SOILS



SAMPLE NO.	ELEVATION OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
1	MISSION CANYON, CALIFORNIA	SANDY GRAVEL (GP)	10.0	NON-PLASTIC		
2	TACOMA, WA	GRAVELLY SAND (SW)	2.0	NON-PLASTIC		
3	HAZLEHURST, MS	CLAYEY SAND (SC)	12.0	21.0	12.0	9.0
4	CENTRALIA, WA	SANDY SILTY CLAY (CL)	30.5	46.0	21.0	19.0
5	VICKSBURG, MS	SILT (ML)	18.0	30.0	26.0	4.0
6	WEST HIGHLANDS, WASHINGTON	CLAYEY SILT (ML)	27.3	33.1	26.7	6.4
7	DALLAS, TEXAS (WALNUT HILLS)	FAT CLAY (CH)	34.9	68.0	27.0	41.0

(from Schomaker and Murdock, 1969, and Lutton, Regan and Jones, 1979)

Certain characteristic points on the grain size curve have been given special attention. The 10-pct-finer point, designated D_{10}, is termed the effective size. The ratio D_{60} (60-pct-finer size) to D_{10} is termed the uniformity coefficient (or coefficient of uniformity) C . These and other parameters derived from the gradation curve are discussed in Peck, Hanson, and Thornburn (1974), the Earth Manual (USBR, 1974), and elsewhere. See also Spigolon and Kelley (1984).

The hydrometer analysis is a slow, somewhat laborious process, and not of overriding importance in most engineering considerations. Soil classification according to the USCS, an important factor in soil-based design, considers only the plasticity characteristics, and not the gradation, of the fines portion of a soil. Hydrometer analysis is sometimes useful in permeability correlations, however.

Manual designations pertaining to mechanical analysis are listed in Table 3-3.

3.2.5.2 Atterberg Limits

Early soil classifications were based only on mechanical composition, but important variations in soil behavior were not accounted for by a strictly mechanical classification. This led A. Atterberg (1911) to develop the simple tests based on moisture content that bear his name. The Atterberg limits are the liquid limit, the plastic limit, and the shrinkage limit (abbreviations: LL, PL, SL) (other symbols have been used such as W_L , W_P , W_S).

Two important points should be kept in mind regarding Atterberg limits. (1) They apply only to fines: either fine-grained soils or the fines portion of graded coarse-grained soils. (2) They concern themselves solely with water content; no other basic soil property is involved. These facts reflect an important fact regarding water in soils. In coarse-grained soils, water is a passing component, which may or may not be present. In fine-grained soils, water is an essential component, which is nearly always present; moreover water plays a fundamental role in determining these soils' behavior.

The Atterberg limits are expressed as numbers, usually not reported to more than two significant figures, representing simply water-content values below and above which different types of behavior prevail. The limits are derived from simple, standardized tests which require a slight amount of personal judgment; hence no greater precision than two significant figures is warranted. The liquid limit states the water content above which a soil behaves like a liquid, but below which it behaves plastically. The plastic limit states the water content below which the soil starts to behave like a solid, and above which it behaves plastically. The shrinkage limit is the water content below which further loss of water by evaporation does not cause a further reduction in volume. Above the SL, changes in water content are associated with changes in volume. Although the Atterberg limits are strictly empirical, there is vast correlation experience with them.

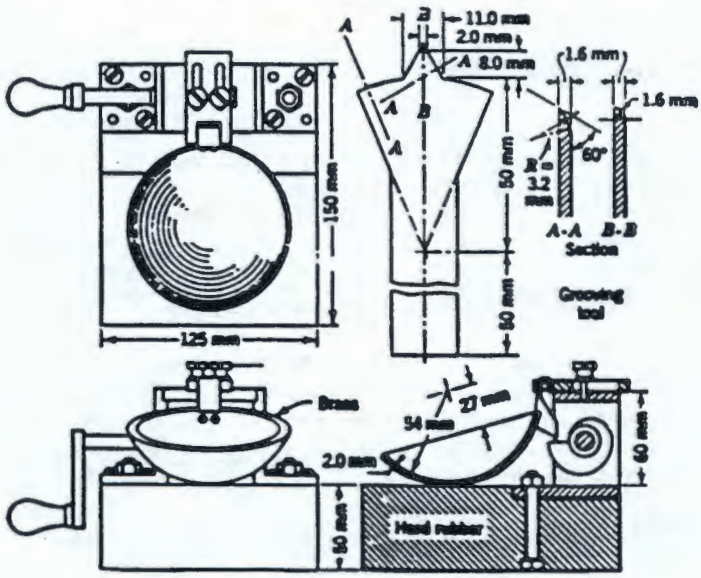
9 3 1 2 9 0 4 0 9 5 4

Since the LL and PL define respectively the upper and lower bounds of plastic behavior, the interval between them may be termed the plastic range. The size of this interval is designated the plasticity index (PI), which is defined simply as the difference between the liquid and plastic limits (PI = LL - PL).

The liquid limit is determined by means of a simple but specially designed laboratory device, shown in Figure 3-8. This device possesses a shallow, bowl-shaped brass cup, into which the moist soil is packed. Into the smoothed surface of the specimen within the cup a groove of specific dimensions is cut with a standardized grooving tool. As the handle is rotated the cup is raised and dropped repeatedly. When a specified length of the groove just closes, the number of drops or blows is recorded; the specimen water content is then determined.

FIGURE 3-8

APPARATUS FOR DETERMINATION OF LIQUID LIMIT



(Note: a slightly different grooving tool is specified by ASTM and AASHTO.) (Courtesy of John Wiley & Sons, Inc.)

To determine the LL a series of tests at different water contents is conducted and a curve of blow count versus water content plotted. The LL is arbitrarily defined as the water content corresponding to 25 blows.

The plastic limit determination involves a simple procedure of rolling a thread of plastic soil between one's hand and a glass plate. When a 1/8-in.-diam thread of soil just begins to crumble, the soil is at its plastic limit.

The shrinkage limit is determined by a procedure involving weights and measured volumes of the soil in a saturated and a dried-out condition. A simple explanation may be found in Taylor (1948). The shrinkage limit is less often used than the other limits.

Atterberg limit tests are also called soil consistency tests. Descriptions of specific procedures for these tests are given in the technical manuals listed in Table 3-3.

3.2.5.3 Water Content and Specific Gravity

Specific test methods for water content and specific gravity of soils are given in the technical manuals listed in Table 3-3. These properties have already been defined and discussed above under "soil properties."

3.2.5.4 Density

Soil density is a function of several factors. A basic factor is the specific gravity of the soil grains. Usually, however, this varies over the narrow range of 2.5 to 2.8. Another factor is the packing or disposition of the soil particles. If soil grains were uniform spheres, their densest possible packing would comprise a void ratio of .35 (26 percent porosity). If smaller spheres were also present, the void ratio would be decreased. It can be appreciated that grain size distribution may noticeably affect soil density. A third factor is the shapes of soil grains. Spheres, either of uniform size or of a gradation of sizes, could be relatively readily vibrated into a dense condition. Sharp, angular particles would more actively resist rearrangement. Platy particles could in principle be stacked very densely if they were all uniformly aligned. From a random orientation, however, it might be very difficult to bring them into a uniform alignment. A fourth factor, water content, strongly affects density as discussed below.

With soil grains of a particular specific gravity, soil density can be increased only by compaction. Compaction involves densification of the grain-to-grain structure and expulsion or compression of trapped air. Increasing the soil density produces several practical and beneficial changes. Stability against future settlement is increased, as the potential for densification has already been partially exhausted. Strength, or resistance to shearing deformation, is increased, because the potential for intergranular movement has been partially exhausted. Permeability is decreased, because in reducing the void ratio the available flow channels have been made smaller.

Various construction methods and equipment are used in practice for soil compaction. Some are better adapted to granular soils, others to fine-grained

cohesive soils. Compacting equipment is discussed later in this Handbook. In general, vibration techniques and smooth-wheeled rollers are better suited to granular soils, and tamping rollers such as sheepsfoot rollers are more adapted to cohesive soils. Smooth-wheeled rollers include machines with both steel wheels and rubber tires. Besides the type of equipment, the weight of the equipment obviously influences the degree of compaction produced.

Two types of laboratory tests are used to determine reference densities of soils, the compaction ("Proctor") test and the relative density or maximum-minimum density test. Good discussions of the principles of these tests and the soil types to which each is applicable are given in the Earth Manual (USBR, 1974) and Peck, Hanson, and Thornburn (1974). In general, the relative density (maximum-minimum) test is applicable to granular, cohesionless, free-draining soils, and the Proctor compaction test is applicable to silty and clayey soils of all types. Both tests provide reference values against which field-achieved densities can be compared and critically evaluated.

The relative density test consists of placing the dry soil in a test container in a loose state and then in a dense state, using previously defined procedures. The densities determined are respectively designated zero and 100 percent relative density. Loose placement is achieved by a specified gentle pouring action, and dense placement by vibration under specified conditions for a specified time. The actual dry bulk densities in the two limiting states are then determined. The relative density of any other specimen of the soil is calculated with a simple formula relating its dry bulk density to the two limiting values (see equation 3.9 above).

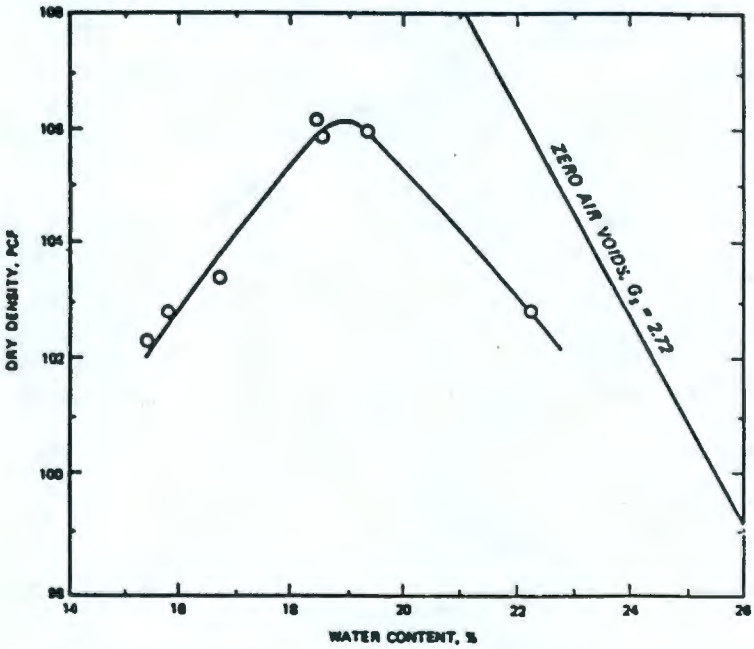
Compacted granular soil is generally used as a bearing member, that is, as a foundation. In a cover system, this would most likely be in the foundation or buffer layer (see below). An accepted lower limit for densified granular soil is 70 percent relative density (Earth Manual, p 280.) References to relative density test procedures are given in Table 3-3.

The compaction or moisture-density test is commonly known as the Proctor test, after R. R. Proctor, who first proposed it in 1933. It is based on the fact that for a given soil and a given compactive effort, the degree of compaction achieved is found to be a function of water content. At some intermediate water content, maximum compaction, as measured by maximum dry density, will be achieved. If the soil is either wetter or drier, the same amount of compactive effort will produce a lower density. An example of this effect is seen in Figure 3-9.

The peak of the compaction curve denotes the <u>optimum water (or moisture) content</u> and the <u>maximum dry density</u> (or dry unit weight). These terms are extensively used in specifications for construction control, as discussed below. A "zero air voids" curve is usually drawn above a compaction curve, as shown in Figure 3-9. Such a curve is readily computed if the specific gravity of the soil grains is known, and represents complete expulsion of air, leaving only water in the soil pores. It represents the upper limit for densification by compaction.

FIGURE 3-9

TYPICAL COMPACTION (MOISTURE-DENSITY) TEST RESULT



(from Standard Proctor test on a CL soil according to Unified soil classification system)

The Standard Proctor test involves 12,375 foot-pounds of compactive effort per cubic foot of soil (a 5.5-lb compacting rod dropped through a height of 12 in. a total of 75 times, that is, 25 blows per lift for each of three lifts, on a soil specimen 1/30 cubic foot in volume). The USBR uses slightly different test dimensions, but the effective effort is the same. Another standardized test, termed the Modified Proctor test, involves approximately 4-1/2 times as much input effort, through a heavier rod and a higher drop. The Standard test, developed by R. R. Proctor, modeled compactive efforts produced by field construction equipment in the early 1930's. The Modified test modeled heavier equipment developed later for use on airfields. An instructive discussion is given by Lutton, Regan and Jones (1979) on the use of tests with lower effort than the Standard Proctor test for modeling the generally lower efforts applied in landfill compaction. References to detailed test procedures are given in Table 3-3.

It is important to remember that a compaction curve, such as Figure 3-9, applies only for a specific compaction method. A different procedure applied to the same soil will shift the curve both vertically and laterally. A

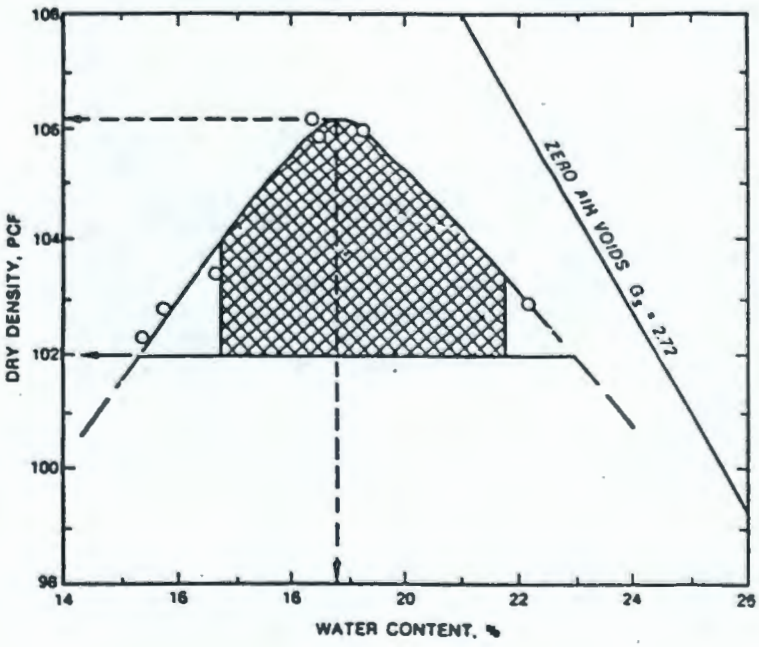
9 3 1 2 9 0 4 0 9 5 8

greater compactive effort will yield a higher maximum dry density at a lower optimum moisture content.

The principle of construction control by means of moisture and density is illustrated by Figure 3-10. Assume that a given soil has been tested in the laboratory by the Standard Proctor test, and that the compaction curve shown is the result. Optimum moisture content is 18.8 pct, and maximum dry density is 106.2 pcf. Assume further that the soil has been tested for some property of interest, say permeability, at different conditions of dry density and water content, and permeability satisfactory for project purposes has been found to exist at dry density greater than 102 pcf and within a moisture range of 16.8 to 21.8 pct. The compaction curve shows that a density of 102 pcf can be achieved, using standard compaction, within the moisture-content range from 15.3 to 22.9 pct. The cross-hatched field in Figure 3-10 indicates the range of acceptable conditions for the compacted soil. Now 102 pcf is 96 percent of 106.2 pcf, the maximum dry density. If performance or end-result specifications are used, they will be written to say that compaction of this soil must be to a minimum of 96 percent of maximum dry density within a range from 2 pct dry to 3 pct wet of optimum moisture content, based on the results of the Standard Proctor compaction test. In this way, laboratory compaction information is translated into simple specifications which the contractor can apply in the field.

FIGURE 3-10

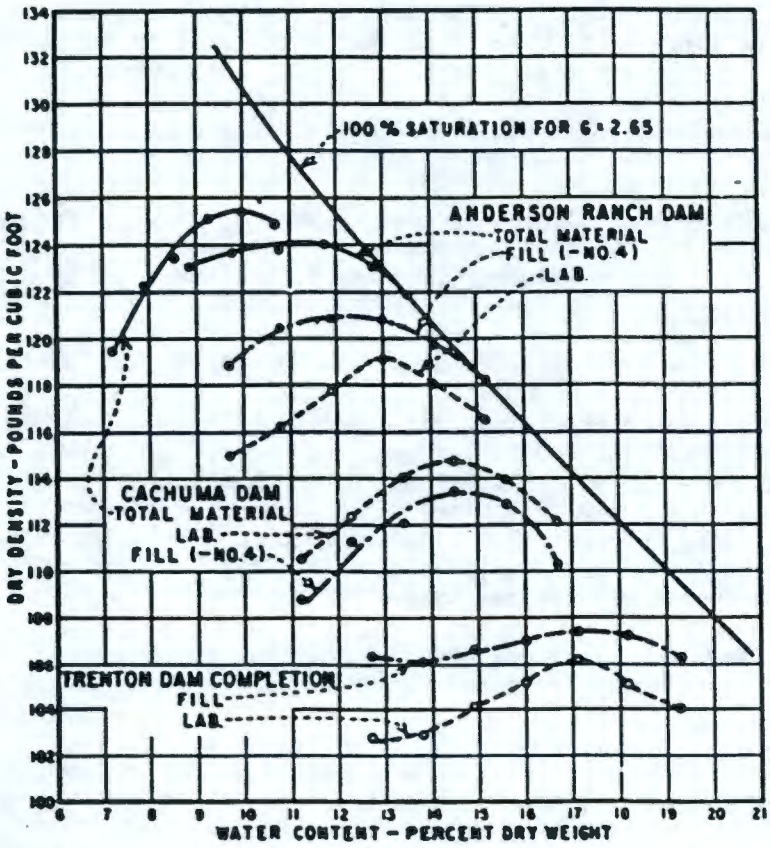
RELATION BETWEEN LABORATORY TEST RESULTS AND STANDARD CONTRACT SPECIFICATIONS FOR COMPACTION (SEE TEXT)



A clear explanation of construction control using compaction tests and criteria is given by Hilf (1974b). Useful discussion of various test methods is given by Spigolon and Kelley (1984). Figure 3-11 represents data from three projects of the USBR. Laboratory compaction curves are compared with curves of actually placed fill. Note that the laboratory curve gives an approximate prediction of field results, but the laboratory curve can be either high or low, relative to the field. Note also the variability of moisture-density relations among the three soils.

FIGURE 3-11

FIELD AND LABORATORY COMPACTION CURVES FOR SOILS PLACED IN DAM EMBANKMENTS OF THREE USBR PROJECTS (FROM HILF, 1974b)



Compacted soils are generally placed at a moisture content near optimum. The following effects are true, however: maximum as-placed soil strength is developed dry of optimum; maximum soil impermeability is developed wet of optimum; maximum density, of course, is at optimum.

9 3 1 2 9 0 4 0 9 6 0

3.2.5.5 Strength

Strength of materials includes tensile, compressive, and shear strengths. Soils effectively have no long-term tensile strength, and since most soils fail in shear, for all practical purposes strength of soils means their shearing strength.

From the cover designer's standpoint, the only reason for concern with soils' shearing strength, other than for trafficability purposes while the cover is being constructed, is where there is a threat of slope failures. Lutton, Regan, and Jones (1979) have discussed the problem of slope stability with regard to cover installations, and reviewed pertinent tests. There is no reason to amplify their discussion in this Handbook, other than to point out one or two general facts.

The subject of slope stability in soils is complicated and has received much study and research. It would be misleading to suggest that a Handbook of this nature could give more than general guidance if a potential slope-instability problem is suspected. A manual dealing with the matter that has been widely used in both governmental and private practice is Department of the Army, 1970.

One simple yet valid statement is that in virtually all cases, water is the leading "bad actor" in causing slope failures. Slopes tend to fail under conditions of high ground moisture. This may be seasonal, due to prolonged rain or heavy snowmelt; it may be situational, as when quick drawdown of a reservoir leaves a saturated earth embankment; it may be a result of poor design, as where slope drainage should have been provided for, but was not.

Taylor (1948) gives a very clear and thorough explanation of the factors involved in slope stability and in the shearing strength of soils. Peck, Hanson, and Thornburn (1974) discuss factors affecting slope stability, and soil strength tests that may be applied in slope-stability studies. They state, however (1974, p 101): "The shear strength of soils, in spite of extensive research, remains a complex and controversial subject; the vast literature is confusing even to the specialist."

In view of the above, it is recommended that any slope-stability problem at a hazardous waste site be referred to a competent and recognized geotechnical expert.

There are many different soil strength tests with varying applications. However, because these tests are not directly applicable to cover soils, they are not listed in this Handbook. For names and designations of soil strength tests the reader should consult the technical manuals listed in Table 3-3.

3.2.5.6 Consolidation

Consolidation refers to a process of densification of a soil under load,

accomplished through a slow escape of water from the pores. It will be of little concern within the soil of a cover system. It may well be of concern in the waste itself, however, or in the soil underlying it. Consolidation is of importance to the foundation engineer, because it controls the settlement that will occur beneath his structures. If some parts of a structure settle more than others (differential settlement), the structure will tend to deform and perhaps crack. Susceptibility to consolidation is termed "compressibility." Consolidation and subsidence of wastes is the subject of current EPA-sponsored research.

Compressibility of soils is tested in a device called the consolidometer, and the test is commonly called the one-dimensional consolidation test. Manual references are cited in Table 3-3.

Consolidation commences when a load, such as a structure, is imposed on a soil. Before the load is placed, the soil is in equilibrium, that is, it is fully consolidated with respect to the force system in effect. The soil is neither settling nor swelling.

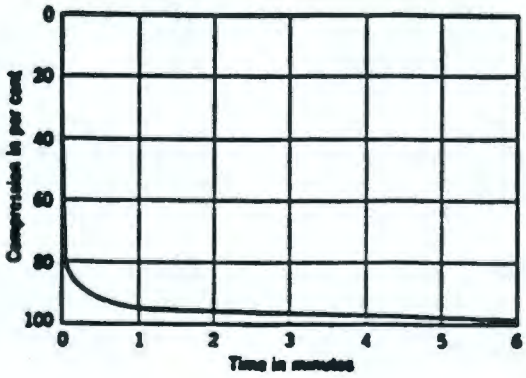
The imposition of a load (or conversely the excavation of a mass of soil) introduces a new force system, and there is an immediate tendency to adjust to it. The process of consolidation commences. The rate of consolidation is controlled directly by the permeability of the soil, whereas the ultimate amount of consolidation is related to the compressibility of the soil skeleton and thus to the nature of the soil particles. As an illustration of the rate effect, see Figure 3-12(a) and (b), showing typical time curves for laboratory consolidation of a sand and clay. The sand responds very fast and the process is nearly complete in a short time. The clay responds much more slowly and the process continues over a long time. In both cases the rate is greatest initially and decreases progressively thereafter.

Because of the direct relation between consolidation rate and permeability, the latter can be computed from data from a consolidation test. This is not commonly recommended, however.

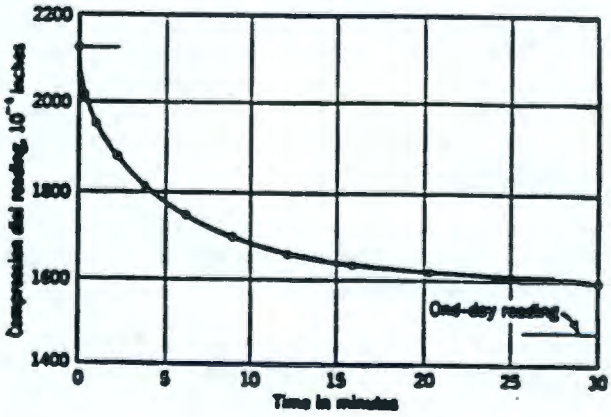
Natural soils have, as a rule, been in place for many years or centuries, and thus are consolidated to equilibrium under their local force system. Waste dumps, on the other hand, were formed relatively recently and are likely still to be in the process of consolidating. Moreover, materials in the waste may be decomposing. Waste dumps may be inherently susceptible to differential consolidation. In a discussion of "inadequate foundations," the Earth Manual (USBR, 1974b) lists several categories, one of which is "talus piles, spoil piles, and dumps." The loose and random manner in which material is placed in these deposits leads to their poor quality as foundations. Unfortunately, uncontrolled waste sites fall directly into this category. Thus subsidence, a recognized serious threat to the integrity of cover systems, is probably to some degree inevitable. Careful placement and compaction of the buffer or foundation layer of the cover system is probably the best way to mitigate the problem.

FIGURE 3-12

TIME CURVES FOR A TYPICAL LOAD INCREMENT IN A LABORATORY CONSOLIDATION TEST: (a) FOR SAND, AND (b) FOR CLAY



(a)



(b)

(from Taylor, 1948; courtesy John Wiley & Sons, Inc.)

3.2.5.7 Permeability

Permeability may be the most important property of cover soils, inasmuch as the principal purpose of the cover system is to act as a roof and retard the inflow of water. Permeability is a measure of the ease with which fluids may flow through a soil. Permeability is related to porosity, the capacity of a soil to hold fluid, but it is related to many other factors as well. Permeability is concerned with time, whereas porosity is not. Permeability is directly analogous to electrical conductivity, thermal conductivity, or similar material properties with regard to any other type of flow.

Permeability has been extensively discussed in the literature of civil engineering, ground-water hydrology, and petroleum engineering. The latter field is concerned with more than one type of fluid, whereas the former two deal in general only with water. When multiple fluids are involved, one must deal with the intrinsic permeability, which is determined only by attributes of the porous medium. Significant attributes are those pertaining to flow channels through the medium: size of channels, their shape with regard to both cross section and tortuosity, surface roughness, and other surface factors such as electrostatic conditions. By channels, of course, is meant the enormous number of possible flow paths within the soil pores. The unit of intrinsic permeability is the darcy, and its dimensions are length squared (e.g., cm^2, ft^2).

When a fluid in contact with soil is capable of reacting with the soil particles, a complicating effect is introduced, since such interaction may actually change the intrinsic permeability by changing the soil structure. This is a subject of great current interest with regard to the use of clay liners for waste or other liquid impoundments.

Rate of flow of a given fluid depends on properties of the fluid, most importantly viscosity, as well as on properties of the medium. By specifying a given fluid at a given temperature, such factors as viscosity and fluid density are fixed, and it becomes possible to define a simple coefficient for the permeability of a given soil to that fluid. The coefficient of permeability is so defined, the fluid being water at 20°C. In ground-water hydrology the term "hydraulic conductivity" is used; it is precisely synonymous with coefficient of permeability as here defined. The conventional symbol in soil mechanics for coefficient of permeability is (lower case) k (in ground-water hydrology, upper case K is used for hydraulic conductivity). The factor k, commonly simply called the permeability, is the (sole) soil-dependent term in the simple equation known as Darcy's law, which describes laminar fluid flow through porous media. Thus Darcy's law is:

$Q = kiA$ with terms as follows:

Q = a volumetric flow rate
k = coefficient of permeability
i = hydraulic gradient
A = an area normal to the mean direction of flow

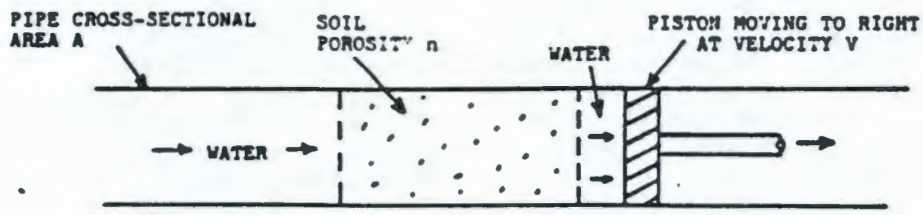
Hydraulic gradient i is a potential gradient, a measure of the driving force associated with the flow. It is the quotient of the difference in (total hydraulic) head between any two points divided by the linear distance between the points.* Being the quotient of two linear quantities, it is dimensionless. As can be seen from the dimensions in Darcy's law, k has the dimensions of a velocity. It is in fact, however, a volumetric flow rate passing through a finite area, and it is well to keep this fact in mind. The velocity identified by a given k is sometimes termed the superficial velocity, in contrast to the seepage velocity, the actual mean speed with which water is moving through the soil. It is a simple matter to understand that the superficial velocity stands to the seepage velocity as the pore volume of the soil stands to the total volume, thus:

$$\frac{V_{superficial}}{V_{seepage}} = n \text{ (= porosity)}$$

This relationship is illustrated in Figure 3-13. Furthermore, it is necessary, strictly speaking, to use the <u>effective</u> porosity, that is, the volume fraction of those pores that actually participate in flow. Particularly in very fine soils, much of the pore space may be effectively "dead storage," as a result of electrostatic or chemical binding of the water in place. Thus the seepage velocity will always be faster, and may be much faster, than the superficial velocity.

FIGURE 3-13

SKETCH SHOWING RELATION BETWEEN DARCY ("SUPERFICIAL") VELOCITY V AND SEEPAGE VELOCITY $V_{SEEPAGE}$



WATER FLOWS TO RIGHT AT VOLUMETRIC FLOW RATE Q.

$Q = V A$. WITHIN SOIL, WATER MOVES TOWARD RIGHT

AT MEAN VELOCITY $V_{seepage} = \frac{1}{n} \cdot V$.

* Among the many explanations of seepage and other hydraulic phenomena in soil, one of the clearest is by Taylor (1948).

In civil engineering k is customarily expressed in centimeters per second. However, several other units are in use. One is the meinzer, used by the U. S. Geological Survey and denoting gallons per day per square foot. Others that may be encountered are inches per hour, feet per day, etc. All permeability units expressed in velocity or volumetric-rate-per-area units can easily be reduced to centimeters per second.

Permeability is a very simple property to conceive but may be a very intricate one to deal with in fact. For one thing, in contrast to many other properties, it varies over enormous ranges. Another difficulty relates to the fact that a measured permeability is an average, describing the average flow over perhaps millions of flow channels. If one large channel develops, as by a crack or erosion of a tube through the soil, the flow may increase suddenly by many-fold. In testing for permeability, it is essential that no anomalous large channel be present. Thus, if a permeability test is carried out in a cylinder, it is essential that no flow-channel be available along the cylinder walls.

Permeability may be and commonly is anisotropic, thus, greater in some directions than others. Permeability relates to flow channels, and thus to the structure of a sediment or soil. Where platy mineral grains are present (recall that the clay minerals form platy grains) there is a tendency toward horizontal orientation. Natural soil deposits commonly show higher permeabilities horizontally than vertically; the factor may be as high as 10^2 or even 10^3 (USBR, 1974b, p 59), although it is usually less (Olson and Daniel, 1981). In natural deposits, gross layering of different beds contributes strongly to the greater horizontal flow capacity. Remolded soils may tend more toward isotropy; but placing and compacting in layers introduces a definite horizontal bias, which works in favor of the cover designer, whose main interest is in reducing vertical permeability.

Consider the effect of thickness of a clay barrier layer. Darcy's law shows that the volumetric flow rate for a given area depends only on permeability and hydraulic gradient. The gradient for percolation is constant at unity. Therefore, the flow rate is a function solely of the permeability. Thus, <u>for steady-state saturated conditions</u>, the same flow rate or flux would pass through a 2-in.-thick layer or a 20-ft layer of the same material. An advancing wetting front, however, would take longer to reach the bottom of the thicker layer, the transit times being proportional to the thicknesses. The rate of movement of a wetting front should correlate approximately with the seepage velocity, mentioned above. The thicker layer, of course, would be more stable and durable. And since steady-state saturated conditions will virtually never really occur, the delay provided by the thicker layer provides more time for drainage of the soil by evapotranspiration and for the beneficial effects of unsaturated flow (discussed below).

Darcy's law is quantitatively valid for saturated flow under laminar conditions. Such conditions represent a state of complete regularity. Deviations from Darcy flow occur in two separate directions. On the high-flow side is turbulent flow, on the low-flow side is unsaturated flow.

9 3 1 2 9 0 4 0 9 9 6 6

Turbulent flow occurs with Reynolds numbers above a certain value (consult texts in soil mechanics or hydraulics). Turbulent flow may occur in very coarse-grained soils, such as the drainage layer of a cover system. Under saturated turbulent flow, the volumetric flow rate falls off fractionally from the Darcian value. Very large flow rates are still likely, and this condition presents no problem.

Unsaturated flow is a much more realistic expectation in cover systems. Unsaturated flow may be conceived of as a situation where only a fraction of the possible flow channels in a soil are being utilized. Measurements of permeability for unsaturated conditions are complicated but have been performed. A typical result of such measurements is shown in Figure 3-14. As the degree of saturation decreases, the apparent permeability of the soil falls off sharply. Just as with the air-bubble effect mentioned below, this effect works to the advantage of the cover designer in practice. A clay cover will probably seldom be completely saturated. Thus the effective permeability of the soil will usually be less than the nominal permeability derived from tests conducted under saturated conditions.

A primary source of error in laboratory permeability measurements is the evolution of air bubbles from the water which block soil pores and artificially reduce permeability. For this reason good laboratory procedure requires the use of deaired water. In practical field use in a cover system, this effect works to the advantage of the cover designer. In fact it may be a prime contributor to the lower effective permeability governing unsaturated flow.

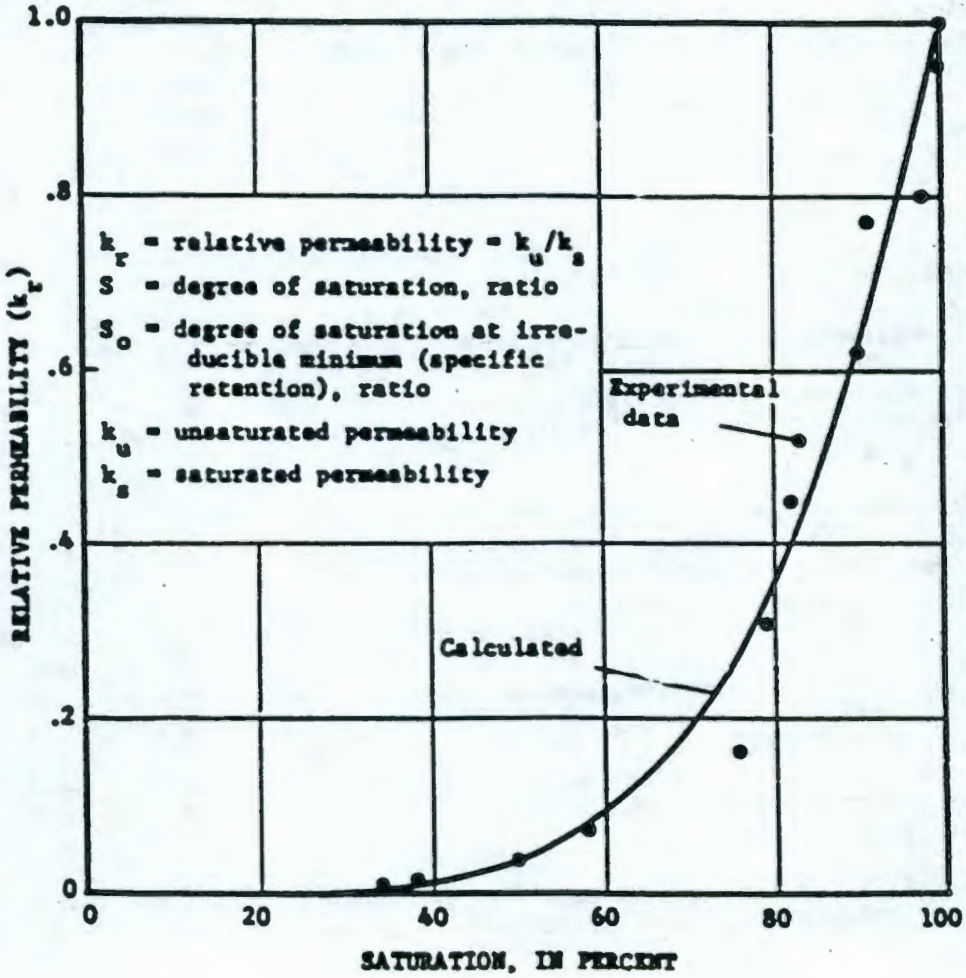
Permeability tests may be made by either the constant-head or the falling-head technique. In the constant-head technique the test is run at steady-state conditions, all the terms in Darcy's equation except k are measured; k is solved for. In the falling-head technique the driving head, and therefore the flow, are both allowed to decay exponentially with time; using the exponential-decay law and making two or more joint measurements of head and time make it possible to compute k. Sketches illustrating the two techniques are given in Lutton, Regan, and Jones (1979) and elsewhere. The constant-head method is appropriate for higher flow rates and thus more pervious soils; the falling-head method is suited to lower flows and less pervious soils.

It may be noted that a permeability test does not involve arbitrary standard procedures, equipment, or numbers (cf. Liquid Limit test, Proctor compaction tests). Therefore, any apparatus that properly measures flows and heads is capable of yielding correct permeability values, so long as complicating factors such as air-bubble evolution and wall leakage are recognized and accounted for. Thus, permeability tests are not as highly standardized as some other tests.

The very small permeability of highly impervious soils may be quite difficult to measure accurately. The situation is somewhat analogous to that of quantitative chemical analysis. Components that are present in parts-per-million or parts-per-billion ranges may require different and more exacting techniques than those present in larger quantities. A listing of published

FIGURE 3-14

EFFECT OF DEGREE OF SATURATION ON PERMEABILITY



Experimental data for permeability of 20-mesh Del Monte sand, and calculated permeability from equation $k_r = \left[(S - S_o)/(1 - S_o)\right]^4$ (from Johnson and Kunkel, 1963)

9 3 1 2 9 0 4 0 9 6 8

permeability-test procedures is given in Table 3-4, but it should be noted that permeability testing is less well standardized than other tests, particularly at the low-permeability end of the range. Before a given test is used, it should be carefully noted for what types of soil that test is valid. For instance, the standard permeability test described by ASTM and AASHTO (see below) is specifically limited to granular soils, down through the range of fine sand and silt. These organizations have no published permeability test pertaining to clays. The current most-favored laboratory test method for permeability of clays involves a rubber confining membrane, similar to that used in triaxial shear tests. This technique is described in USCE (1980). Permeability of clays may also be measured in the consolidometer (USCE, USBR). Several papers dealing with permeability measurement were presented at an ASTM symposium on impermeable barriers for soil and rock held in June 1984 in Denver, CO.

More reliable information on permeability may be derived from field than from laboratory tests. The tests in Table 3-4 include three field tests, all from the Earth Manual (USBR, 1974b). These tests are simple, and have limitations as mentioned by Auvinet and Espinosa (1981); moreover they take time, and require the extended presence of a technician in the field. Nevertheless, their use may be warranted. Field permeability may also be measured using methods developed by Hvorslev (1949) and presented in Lambe and Whitman (1969).

The special difficulty in measuring very low soil permeabilities was acknowledged by ASTM with the publication of Special Technical Publication 746, "Permeability and Groundwater Contaminant Transport" (Zimmie and Riggs, 1981), devoted to the subject. A paper in this volume by Olson and Daniel (1981) addresses directly the problem of measurement of low permeabilities, discussing pitfalls and problems as well as various methods that have been used. Another paper in the volume (Auvinet and Espinosa, 1981) describes a case history of the design and construction, including permeability testing, of a clay-lined cooling pond. In the opinion of the preparers of this Handbook, the insights provided in Auvinet and Espinosa's paper are especially enlightening for anyone concerned with the field use of compacted clay in a water-retarding application.

Permeability test procedures described in standard manuals are listed in Table 3-4. Conversion factors between various permeability units may be found in Table 3-5.

TABLE 3-4

STANDARD PERMEABILITY TESTS

Manual	Designation	Title of Test
ASTM	D-2434	Permeability of Granular Soils (Constant Head)
AASHTO	T-215	Permeability of Granular Soil (Constant Head)
USBR	E-13	Permeability and Settlement of Soils
USBR	E-14	Permeability and Settlement of Soils Containing Gravel
USBR	E-15	One-dimensional Consolidation of Soils[a]
USBR	E-18	Field Permeability Tests in Boreholes
USBR	E-19	Field Permeability Test (Well Permeameter Method)
USBR	E-36	Field Permeability Test (Shallow-well Permeameter Method)
USCE	App. VII (3)	Constant-head Permeability Test with Permeameter Cylinder
USCE	App. VII (4)	Falling-head Permeability Test with Permeameter Cylinder
USCE	App. VII (5)	Permeability Tests with Sampling Tubes[b]
USCE	App. VII (6)	Permeability Tests with Pressure Chamber
USCE	App. VII (7)	Permeability Tests with Back Pressure
USCE	App. VII (8)	Permeability Tests with Consolidometer[c]

[a]A subsection of USBR E-15 contains directions for computing permeability by the falling-head method.

[b]USCE App. VII (5) pertains to undisturbed soil samples.

[c]Not recommended.

9 3 1 2 9 0 4 0 9 7 0

TABLE 3-5

PERMEABILITY CONVERSION FACTORS[a]

	cm per s	ft per Day	ft per Year	Darcy	Meinzer, gallons per day per ft^2	in. per hr
cm per s	1	2.835×10^3	1.0348×10^6	1.033×10^3	2.12×10^4	1.42×10^3
ft per day	3.53×10^{-4}	1	365	3.64×10^{-1}	7.48	0.5
ft per year	9.67×10^{-7}	2.74×10^{-3}	1	9.99×10^{-4}	2.05×10^{-2}	1.37×10^{-3}
Darcy	9.68×10^{-4}	2.75	1.001×10^3	1	20.50	1.37
Meinzer gallons per day per ft^2	4.72×10^{-5}	1.34×10^{-1}	48.8	4.88×10^{-2}	1	6.70×10^{-2}
in. per hr	7.06×10^{-4}	2	729	7.29×10^{-1}	14.9	1

[a]Multiply the unit at the left by the number in the column to get the unit at the top of the column. All units are based on a temperature of 60°F or 15.6°C (from Johnson, 1981).

3.2.5.8 Shrink/Swell Behavior; Activity

Certain clayey soils have a high tendency to swell on wetting and shrink on drying. Such behavior correlates with a clay-mineral property known as activity.

$$A = \frac{PI}{C}$$

where PI is plasticity index and C is percent clay-size material (<2 μm), or,

$$A = \frac{PI}{C - n}$$

with n varying between 5 and 10 (Mitchell, 1976). The activity of clays varies from 0.1 to 7, as shown by Table 3-6. However, virtually all of the upper range is occupied by smectites (smectite is effectively synonymous with montmorillonite). Active clays mean highly expansive, highly compressible soils. Where such soil is used in a cover system, there is a potential for disruption through cracking on drying.

Expansive soils are generally well known in the areas where they occur from construction problems with foundations and highways. The great preponderance of such soils classify as CH in the USCS (discussed below). Suggestions for dealing with expansive soils in landfill cover applications are given by Lutton, Regan, and Jones (1979). Research on identification of such soils was reported by Snethen, Johnson, and Patrick (1977). For the highway engineer, Ogiesby (1975, pp 447, 518) recommends, for clay soils, compaction somewhat wet of optimum and to no greater than about 90 percent of Standard

TABLE 3-6

ACTIVITIES OF VARIOUS MINERALS[a]

Mineral	Activity[b]
Smectites	1-7
Illite	0.5-1
Kaolinite	0.5
Halloysite ($2H_2O$)	0.5
Halloysite ($4H_2O$)	0.1
Attapulgite	0.5-1.2
Allophane	0.5-1.2

[a]From Mitchell (1976).

[b]Activity, $A = \frac{\text{Plasticity Index}}{\% < 2\ \mu m}$

AASHTO (Standard Proctor) density, in order to avoid postconstruction swelling.

Standardized tests of shrink/swell behavior of soils are listed in Table 3-3.

3.2.5.9 Dispersivity

Certain clays show a property known as dispersivity. This is a tendency to go into colloidal suspension, and thus to erode very readily. On a micro scale, clay particles change from a flocculated to a dispersed state. Nondispersive soil in contact with flowing water requires a certain threshold velocity before it will start to erode. Dispersive soil, in contrast, requires no threshold velocity; colloidal particles pass spontaneously into suspension in still water.

Dispersive soil is a serious problem in some earthfill dams, where piping erosion can lead to failure. In a cover system dispersivity involves mainly a threat of soil erosion, either surface erosion or internal erosion where, in a layered cover, a layer of dispersive fine-grained soil might be in contact with a granular, pervious soil.

The transfer between flocculated and dispersed states is an electrochemical surface process and is sensitive to the chemistry of both the clay minerals and the pore fluid. Dispersivity appears to be associated with sodium saturation of clay-mineral surfaces. Given such surface saturation, the natural pore fluid of such a soil will be sodium-rich. When this soil is exposed to either pure water or a dilute solution low in dissolved sodium, ion

9 3 1 2 9 0 4 0 9 7 2

exchange, flushing of the adsorbed sodium, and dispersive erosion tend to follow.

Dispersivity is not revealed by common engineering soil indices such as Atterberg Limits. Clues to dispersive soil may be found locally in the form of deep gully or tunnel erosion of exposed soil surfaces. Several tests have been developed, which are simple, inexpensive, and quite reliable. These are the pinhole test; saturation extract analysis; Soil Conservation Service (SCS) dispersion ("double hydrometer") test; and crumb test. Descriptions and discussions of these tests may be found in Sherard, Dunnigan, and Decker (1976), Mitchell (1976), papers in Sherard and Decker (1977). The pinhole test may be found in USCE (1980 revision; Appendix XIII). The pinhole test is commonly regarded as the most reliable single test, but several authors in Sherard and Decker (1977) recommend corroboration by more than one test method, particularly in view of the simplicity of the test procedures. The crumb test, for example, involves simply dropping a crumb of soil into a beaker of water and observing its reaction.

Two techniques have been used successfully to counter the erosive effects of dispersive soils. One is treatment with hydrated lime; the other is the use of graded filters where the threat of internal erosion exists within an earthfill dam. Possible dispersive-soil problems in a cover system should be amenable to treatment by one or both of these techniques. Lime may have the side effect of increasing permeability, however.

The cover designer should be aware of the threat of dispersive behavior when using bentonite to amend a soil to achieve impermeability. The high-swelling Wyoming bentonite that is most desired as a sealant contains sodium-saturated clay and is subject to the dispersive tendencies mentioned above. When bentonite is used, the gradation of the material used with it is very important. It is necessary to achieve a filter effect by having sufficient granular fines to stabilize the bentonite against dispersive erosion. D'Appolonia (1980) reports on the danger of piping failures where such a precaution is not followed. According to D'Appolonia (p 415) the use of bentonites treated with certain polymers may also assist in preventing piping failures. Since bentonite contains highly active clay minerals, it is also susceptible to attack by organic solvents or other chemicals that may be present in wastes. Bentonite is further discussed below in section 3.3.1.2.

3.2.5.10 Other Soil Properties and Tests

Other soil properties and tests may be of interest for specialized purposes. Soil information required for the purposes of designing for vegetation is discussed in section 4.3 below. Factors that may be of interest include soil reaction (pH), cation exchange capacity, and organic content. The reader is referred to Black (1965) for technical information on soil analysis or testing for agricultural purposes. The discussion above under permeability suggests the relative complexity of water-related phenomena in unsaturated soils. For a discussion of capillary phenomena, the interested reader is referred to the discussion of capillarity in Taylor (1948). Other sources

(e.g., Snethen, Johnson, and Patrick, 1977a; Brady, 1974) explain the phenomenon known as soil suction. Many of the specific behavioral complexities of a soil relate to its mineralogical composition. Mineralogical analysis of fine-grained soil is complicated. Qualitative and semiquantitative analyses are relatively reliable, but quantitative mineralogical analysis of clays achieves nowhere near the precision of chemical analysis or even of mineralogical analysis of coarser-grained aggregations. The chief analytical methods are X-ray diffraction and differential thermal analysis; these are explained in Mitchell (1976) and elsewhere. Mineralogical analyses should be undertaken by specialized laboratories.

3.2.6 Engineering Characteristics of Soil Types

Rankings and evaluations of the various USCS Groups have been made for various purposes. Table 3-7 shows an evaluation with regard to use in roads and airfields, prepared by the U. S. Army Engineer Waterways Experiment Station. Table 3-8 shows an evaluation and ranking with regard to earth dams and associated features, prepared by the U. S. Bureau of Reclamation. Table 3-9 shows a set of rankings prepared by Lutton, Regan, and Jones (1979) for categories of engineering behavior that are pertinent to cover systems. Since these authors were concerned with municipal as well as hazardous waste disposal sites, several categories appear in Table 3-9 that are not discussed in this Handbook.

Table 3-10 summarizes soil properties obtained in more than 1500 soil tests performed by the Bureau of Reclamation, arranged according to soil classification groups, including frequently occurring boundary groups (Hilf, 1974a). Most of the soils were from the western United States; some were from foreign sources. The geographical distribution is not believed to have affected the classifications.

The cover designer considering the use of soils for construction of the various components of a cover system, as discussed below in Chapter 4, can refer to these tables for information as to which types of soil are best suited for which components of the system. However, it should be clearly understood that for design purposes, material properties for the specific site in question must be used, rather than general properties from these or any other tables.

3.3 Soil Additives

Soil additives refer to manufactured commercial products, specially processed natural materials, or the by-products of a commercial process that, when added in the proper quantities, will improve the characteristics and performance of a soil. Generally, soil additives are employed to improve the soil's performance in the areas of stability and permeability. Stabilization involves the process of blending or mixing an additive with a soil to improve or control the volume, stability, strength, stress-strain characteristics, and/or

9 3 1 2 9 0 4 0 9 7 4

TABLE 3-7

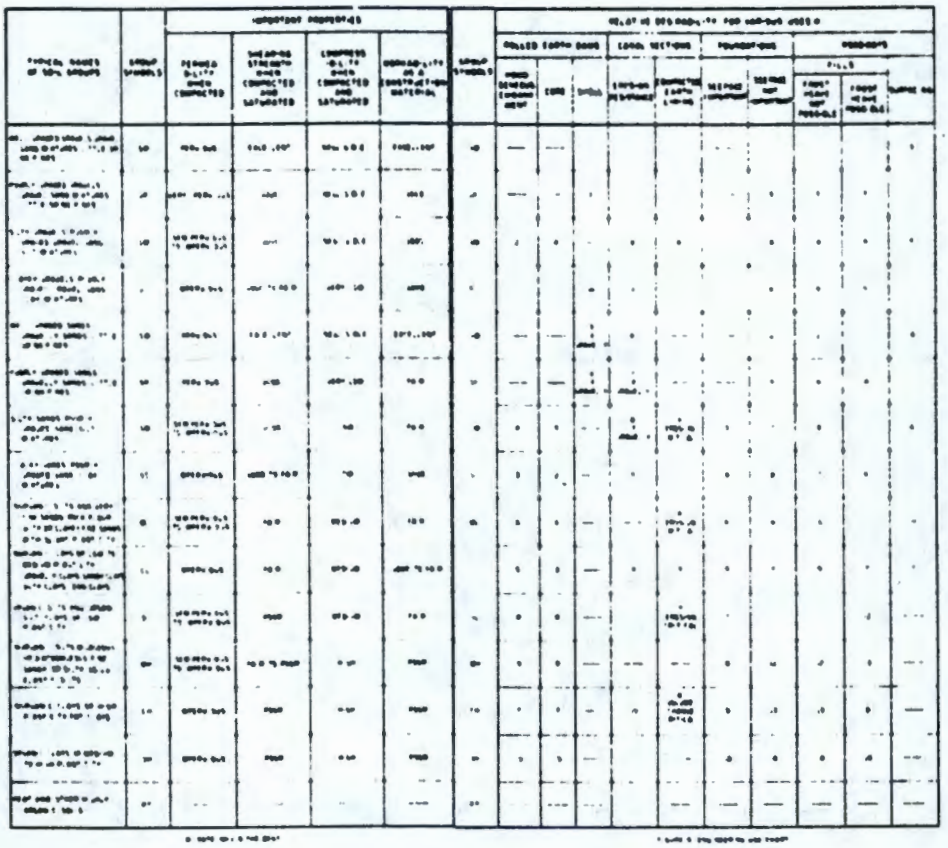
CHARACTERISTICS OF USCS SOIL GROUPS PERTINENT TO ROADS AND AIRFIELDS

Major Divisions (1)		Symbol: Letter (2)	Symbol: Graphic (3)	Symbol: Color (4)	Name (5)	Value as Subgrade When Not Subject to Frost Action (7)	Value as Subbase When Not Subject to Frost Action (8)	Value as Base When Not Subject to Frost Action (9)	Potential Frost Action (10)	Compressibility and Expansion (11)	Drainage Characteristics (12)	Compaction Equipment (13)	Unit Dry Weight lb per cu ft (14)	Typical Properties: CBR (15)	Typical Properties: k lb per cu in. (16)
[illegible]	[illegible]	GW	[illegible]	[illegible]	Well graded gravels or gravel-sand mixtures, little or no fines	Excellent	Excellent	Good	None to very slight	Almost none	Excellent	Crawler type tractor, rubber-tired roller, vibratory roller	125-140	40-80	300-500
		GP	[illegible]		Poorly graded gravels or gravel sand mixtures, little or no fines	Good to excellent	Good	Fair to good	None to very slight	Almost none	Excellent	Crawler type tractor, rubber-tired roller, vibratory roller	110-140	30-60	200-500
		GM	[illegible]	[illegible]	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Good	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	120-145	40-80	200-500
						Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	110-135	20-40	200-500
		GC	[illegible]		Clayey gravels, gravel-sand-clay mixtures	Good	Fair	Poor to not suitable	Slight to medium	Slight	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	110-145	20-40	200-500
	[illegible]	SW	[illegible]	[illegible]	Well graded sands or gravelly sands, little or no fines	Good	Fair to good	Poor	None to very slight	Almost none	[illegible]	Crawler-type tractor, rubber-tired roller	110-130	20-40	200-500
		SP	[illegible]		Poorly graded sands or gravelly sands, little or no fines	Fair to good	Fair	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired roller	100-120	10-40	15-[illegible]
		SM	[illegible]	[illegible]	Silty sands, sand-silt mixtures	Fair to good	Fair to good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	120-135	15-40	150-[illegible]
						Fair	Poor to fair	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-130	10-20	100-150
		SC	[illegible]		Clayey sands, sand-clay mixtures	Poor to fair	Poor	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired roller, sheepsfoot roller	100-135	5-20	100-150
[illegible]	[illegible]	ML	[illegible]	[illegible]	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Poor to fair	Not suitable	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired roller, sheepsfoot roller, close control of moisture	90-130	15 or less	[illegible]
		CL	[illegible]		Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Poor to fair	Not suitable	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired roller, sheepsfoot roller	90-130	15 or less	50-150
		OL	[illegible]		Organic silts and organic silt-clays of low compressibility	Poor	Not suitable	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired roller, sheepsfoot roller	[illegible]	5 or less	[illegible]
	[illegible]	MH	[illegible]	[illegible]	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller, rubber-tired roller	[illegible]	10 or less	[illegible]
		CH	[illegible]		Inorganic clays of high plasticity, fat clays	Poor to fair	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	[illegible]	15 or less	50-150
		OH	[illegible]		Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller, rubber-tired roller	[illegible]	5 or less	[illegible]
[illegible]		Pt	[illegible]	[illegible]	Peat and other highly organic soils	Not suitable	Not suitable	Not suitable	Slight	Very high	Fair to poor	Equipment not practical	-	-	-

From "The Unified Soil Classification System" (Geotechnical Laboratory, 1982)

TABLE 3-8

ENGINEERING USE CHART FOR USCS SOIL GROUPS, WITH EMPHASIS ON EARTH DAMS AND RELATED FEATURES



Earth Manual (U.S. Bureau of Reclamation, 1974b)

TABLE 3-9

RANKING OF UNIFIED-SYSTEM (USCS) SOIL GROUPS WITH REGARD TO COVER-RELATED ENGINEERING BEHAVIOR*

Best group appears first, worst group appears last; groups separated by commas have equal rank.

Trafficability, GO/NO-GO:	GW, GP, SW, SP; SM; GM; SC; GC; CH; CL; MH; ML; OL; OH; Pt
Trafficability, Stickiness:	GW, GP; SW, SP; GM; SM; ML; OL; GC; SC; CL; MH; CH
Trafficability, Slipperiness:	GW, GP; SW, SP; GM; SM; GC; SC; ML, OL; CL; MH; CH
Impede Water Percolation:	CH; CL; MH; ML; GC; SC; GM; SM; SW; GW; SP; GP
Assist Water Percolation:	GP; SP; GW; SW; SM; GM; SC; GC; ML; MH; CL; CH
Impede Gas Migration:	CH; CL; ML; GC; SC; SM; SP, GM; SW; GP; GW
Assist Gas Migration:	GW; GP; SW; GM, SP; SM; SC; GC; ML; CL; CH
Fire Resistance:	CH; CL; ML; GC; SC; SM; SP, GM; SW; GP; GW
Water-erosion Resistance:	GW, GP; SW, SP; GC; GM; Pt; SM; SC; OH; CH; MH; OL; CL; ML
Wind-erosion Resistance:	GW, GP; SW, SP; GM; SM; GC; SC; ML, OL; CL; MH; CH
Dust Control:	GW, GP; SW, SP; GM; SM; GC; SC; ML, OL; CL; MH; CH
Crack Resistance:	GW, GP, SW, SP; SM; GM; SC; GC; ML; OL; CL; OH, MH; CH
Reduce Freeze Action: Fast Freeze:	CH; CL; ML; GC; SC; SM; GM, SP; SW; GP; GW
Reduce Freeze Action: Saturation:	GW, GP; SW, SP; CH; GM; SM; SC; GC; CL, OL; MH; ML
Side Slope - Seepage:	CH; CL; MH; ML; GC; SC; GM; SM; SW; GW; SP; GP
Side Slope - Drainage:	GP; SP; GW; SW; SM; GM; SC; GC; ML; MH; CL; CH
Discourage Burrowing:	GW, GP; SW, SP; GM; SM; GC; SC; ML, OL; CL; MH; CH
Impede Vector Emergence:	CH; MH; CL; SC; GC; ML, OL; SM; GM; SP, SW; GP, GW
Support Vegetation:	SC; SM; Pt, ML; MH, OL; GC; GM; CL; CH, OH; SP, SW; GP, GW
Future Use, Natural:	SC; SM; Pt, ML; MH, OL; GC; GM; CL; CH, OH; SP, SW; GP, GW
Future Use, Foundation:	GW, GP, SW, SP; SM; GM; SC; GC; CH; CL; MH; ML; OL; OH; Pt
Side Slope Stability:	"determine on basis on laboratory testing"
Discourage Birds:	"all soils are suitable"

* After Lutton, Regan, and Jones (1979); see text.

TABLE 3-10

AVERAGE PROPERTIES OF SOILS[a]

Soil Classification Group	Proctor Compaction: Maximum Dry Density In Pounds Per Cubic Foot	Proctor Compaction: Optimum Water Content, Percent	Void Ratio, e_o	Permeability, k, Feet Per Year	Compressibility: @ 20 p.s.i., Percent	Compressibility: @ 50 p.s.i., Percent	Shearing Strength: C_o p.s.i.	Shearing Strength: C_{sat} p.s.i.	tan ϕ
GW	>119	<13.3	(*)	27,000± 13,000	<1.4	(*)	(*)	(*)	>0.79
GP	>110	<12.4	(*)	64,000± 34,000	<0.8	(*)	(*)	(*)	>0.74
GM	>114	<14.5	(*)	>0.3	<1.2	<3.0	(*)	(*)	>0.67
GC	>115	<14.7	(*)	>0.3	<1.2	<2.4	(*)	(*)	>0.60
SW	119±5	13.3±2.5	0.37±*	(*)	1.4±*	(*)	5.7±0.6	(*)	0.79±0.02
SP	110±2	12.4±1.0	0.50±0.03	<15.0	0.8±0.3	(*)	3.3±0.9	(*)	0.74±0.02
SM	114±1	14.5±0.4	0.48±0.02	7.5±4.8	1.2±0.1	3.0±0.4	7.4±0.9	2.9±1.0	0.67±0.02
SM-SC	119±1	12.8±0.5	0.41±0.02	0.8±0.6	1.4±0.3	2.9±1.0	7.3±3.1	2.1±0.8	0.66±0.07
SC	115±1	14.7±0.4	0.48±0.01	0.3±0.2	1.2±0.2	2.4±0.5	10.9±2.2	1.6±0.9	0.60±0.07
ML	103±1	19.2±0.7	0.63±0.02	0.59±0.23	1.5±0.2	2.6±0.3	9.7±1.5	1.3±*	0.62±0.04
ML-CL	109±2	16.8±0.7	0.54±0.03	0.13±0.07	1.0±0.2	2.2±0.0	9.2±2.4	3.2±*	0.62±0.06
CL	108±1	17.3±0.3	0.56±0.01	0.08±0.03	1.4±0.2	2.6±0.4	12.6±1.5	1.9±0.3	0.54±0.04
OL	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)
MH	82±4	36.3±3.2	1.15±0.12	0.16±0.10	2.0±1.2	3.8±0.8	10.5±4.3	2.9±1.3	0.47±0.05
CH	94±2	25.5±1.2	0.80±0.04	0.05±0.05	2.6±1.3	3.9±1.5	14.9±4.9	1.6±0.86	0.35±0.09
OH	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)	(*)

[a]Based on USBR experience; see text. From Hilf (1974a).

The ± entry indicates 90 percent confidence limits of the average value.

* Denotes insufficient data, > is greater than, < is less than.

Note: One foot per year equals approximately 10^{-6} centimeters per second (precisely, 9.665×10^{-7} cm/sec).

durability of that soil. An additive modifies the permeability of a soil by altering the soil's pore size and/or pore size distribution or by creating a cemented structure within the soil.

A requirement to use a soil additive is more likely where a multilayered cover system is constructed. The multilayered cover concept is discussed in Chapter 4. Elements of a cover system that might employ soil additives for these purposes are the foundation layer and the barrier layer. A site's inability to provide a stable surface on which to construct an appropriate cover may in some cases be overcome through the utilization of the proper soil additive. Likewise some materials' applicability as a barrier to percolating water may be enhanced with the use of an appropriate additive.

3.3.1 Common Soil Additives and Their Applications

The most commonly used soil additives are bentonite, lime, portland cement, fly ash, and bituminous materials. In the selection of one or more of these additives, certain factors must be considered which will ultimately determine their effectiveness. These factors are: purpose for improving the soil, soil type, degree of soil quality improvement desired, and environmental conditions (geochemical nature of site, weather, etc.). The chemical nature of the wastes should also be considered in selecting a soil additive.

With the exception of bentonite, each of the above-mentioned soil additives has been used for both stabilization and impermeabilization. Bentonite serves only to decrease a soil's permeability.

3.3.1.1 Soil Stabilization

For stabilization Figure 3-15 and Table 3-11 provide initial guidance in selecting a bituminous material, portland cement, lime, or lime/cement/fly-ash mixture. Enter Figure 3-15 with the percentages of gravel, sand, and fines; determine the area (1A, 2C, 3, etc.) where the intersection of these three percentages lies. Given this area number, refer to Table 3-11 for guidance for the initial selection of the best-suited additive. Note the restrictions in Table 3-11 regarding Atterberg limits and gradation. For example, a soil containing 60 percent gravel, 30 percent sand, and 10 percent fines falls within area 2B of Figure 3-15. Table 3-11 indicates that bituminous materials, lime, and lime/cement/fly-ash could be considered. Portland cement is eliminated, as only 40 percent of the material passes the No. 4 sieve. If soil tests indicate a PI of 17, then lime or a combination of lime, cement, and fly ash will be the better additive for stabilization. However, this is initial guidance only, and the best additive can only be determined by laboratory studies such as those outlined in "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982).

FIGURE 3-15

CHART FOR SELECTING SOIL-STABILIZING ADDITIVES
(TO BE USED WITH TABLE 3-10)

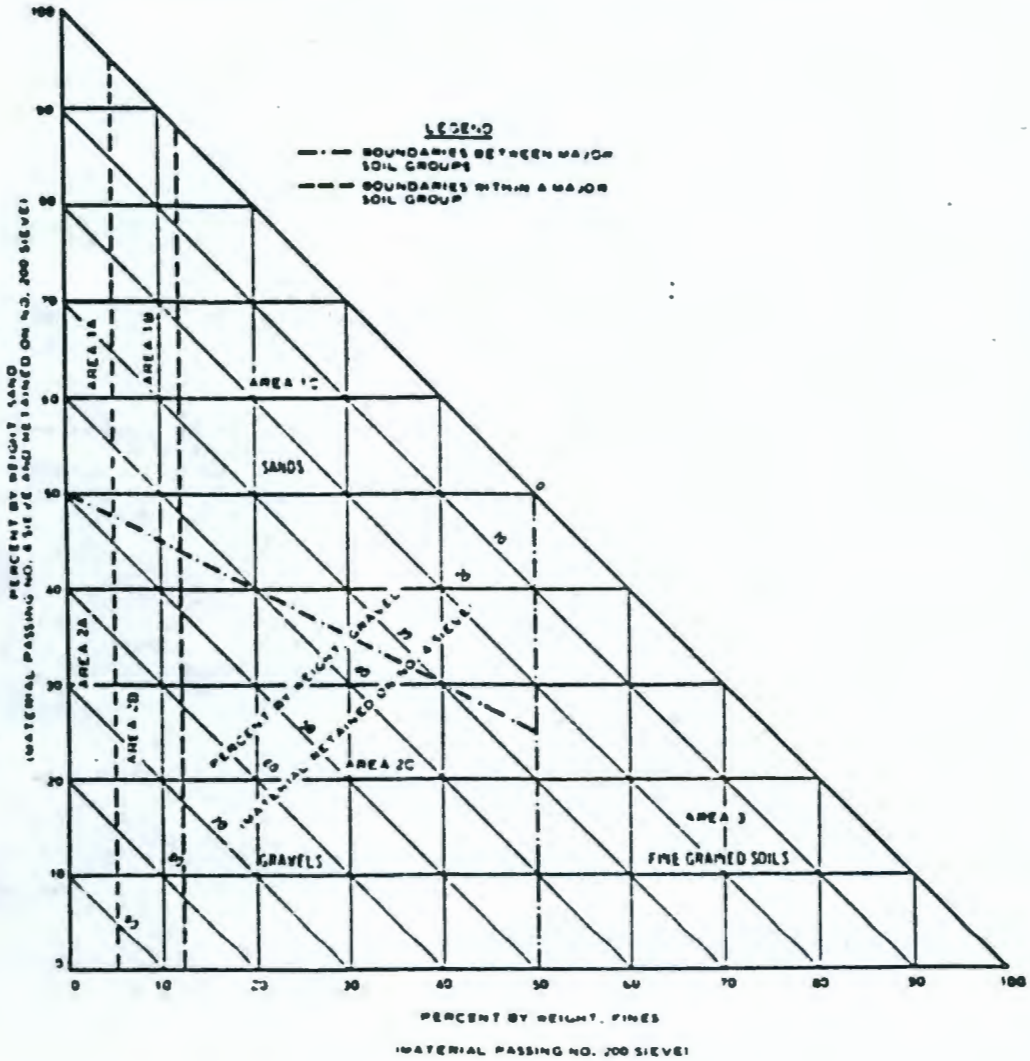


TABLE 3-11

GUIDE FOR SELECTING A STABILIZING ADDITIVE

Area	Soils Class.	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	Restriction on Percent Passing No. 200 Sieve	Remarks
1A	SW or SP	(1) Bituminous			
		(2) Portland Cement			
		(3) Lime-Cement-Fly Ash	PI not to exceed 25		
1B	SW-SM or SP-SM or SW-SC or SP-SC	(1) Bituminous	PI not to exceed 10		
		(2) Portland Cement	PI not to exceed 30		
		(3) Lime	PI not less than 12		
		(4) Lime-Cement-Fly Ash	PI not to exceed 25		
1C	SM or SC or SM-SC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	
		(2) Portland Cement	---[b]		
		(3) Lime	PI not less than 12		
		(4) Lime-Cement-Fly Ash	PI not to exceed 25		
2A	GW or GP	(1) Bituminous			Material should not be uniform-graded.
		(2) Portland Cement			Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime-Cement-Fly Ash	PI not to exceed 25		
2B	GW-GM or GP-GM or GW-GC or GP-GC	(1) Bituminous	PI not to exceed 10		Well-graded material only
		(2) Portland Cement	PI not to exceed 30		Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime	PI not less than 12		
		(4) Lime-Cement-Fly Ash	PI not to exceed 25		
2C	GM or GC or GM-GC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	Well-graded material only
		(2) Portland Cement	---[b]		Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime	PI not less than 12		
		(4) Lime-Cement-Fly Ash	PI not to exceed 25		
3	CH or CL or MH or ML or OH or OL or ML-CL	(1) Portland Cement	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
		(2) Lime	PI not less than 12		

[a]Restriction on liquid limit (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

[b]$PI \leq 20 + \frac{50 - \text{percent passing}}{4}$

Source: "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982).

3.3.1.2 Permeability Reduction

Bentonite, portland cement, lime, fly ash, and bituminous materials have all been used in modifying the permeability of soils. Cement, fly ash, lime, and combinations of them reduce the permeability of a granular soil through cementation at interparticle contacts and by increasing the percent fines in the material. The disadvantage of these additives is that a relatively rigid layer is formed, which is susceptible to damage from settlement or heave. Therefore, a stable base must be provided to insure the integrity of a hydraulic barrier constructed using a cement-, fly-ash-, or lime-modified soil. Although the various types of bituminous additives provide a greater degree of flexibility, soils modified with them are still vulnerable to the effects of differential settlement. Also, the use of bituminous materials is normally restricted to coarse-grained soils or soils that pulverize easily.

The addition of lime to a clayey soil typically <u>increases</u> that soil's permeability.

Bentonite is a natural material rich in montmorillonite-type clay. Montmorillonite is distinguished from other clay minerals by its extreme fineness, high water absorbency, and swelling characteristics upon coming into contact with water. This swelling characteristic enables a soil-bentonite layer or bentonite membrane to demonstrate a "self healing" action. By this it is meant that some of the cracks that form in a soil-bentonite or bentonite-only membrane (due to installation practices, subsidence, or drying) will close upon coming into contact with infiltrating water. In this respect, bentonite possesses a distinct advantage over relatively stiffer materials such as soil cement and asphalt concrete. However, bentonite is not without problems. The performance of bentonite is greatly affected by the quality and type of bentonite. Some deposits have been found to contain sand, silt, and other clays. Generally, a Wyoming type bentonite has been found to be satisfactory over the years from the standpoint of impurities. Also bentonite has experienced problems with piping and diffusion through sands and gravels (with large pore channels). Studies have shown that sodium bentonite is significantly affected if placed in an environment rich in calcium ions (CRREL, 1978; also see discussion under "dispersivity," sec. 3.2.4.9 above). Calcium-sodium ion exchange can have a pronounced effect on bentonite's ability to act as a sealant. Organic solvents and other nonpolar chemicals can also have a harmful effect on bentonite.

3.3.2 Soils Suitable for Stabilization/Modification

The type of soil to be modified will usually dictate the feasibility of using certain soil additives. Generally, the ease with which an additive can be blended into a soil is a function of the soil type. For many additives (particularly bitumen and cement) the degree to which they can be uniformly distributed in the soil will be critical to their performance. As a rule of thumb, as the PI and percent fines in a soil increase, the pulverization of that material becomes more difficult. As pulverization becomes more

difficult, the harder it becomes to obtain a uniform distribution of the additive. In general, bituminous materials and portland cement work best in coarse-grained soils that pulverize easily, while lime is usually used on fine-grained soils, as it lowers the PI of the soils to which it is added.

The detailed guidance in Table 3-11 is in accord with these rules of thumb.

3.3.3 Soil Blending

Although not involving a soil additive as such, the process of blending one type of soil with another does touch on the purposes of using soil additives. By combining soils with different gradations it may be possible to obtain a material meeting the desired specifications for stability and/or impermeability. Through the addition of coarse- and/or fine-grained soil, a well-graded material having improved strength and drainage characteristics may sometimes be obtained.

3.4 Nonsoil Materials

3.4.1 General

"Nonsoil materials" as used here, refer to any materials or supplies (e.g., pipes), other than a natural soil, that may be used in the design and construction of a cover system. These include several materials mentioned above as soil additives. Others discussed below include materials that serve to form an impermeable component of the cover system; bulk materials potentially useful in construction, originating as industrial wastes or residues; materials and supplies that serve special functions, such as drainage pipes and tiles; and permeable synthetic fabrics known as "geotextiles" which serve a variety of engineering functions including strengthening, stabilizing, and separating soils.

3.4.2 Impermeable Materials

Impermeable materials restrict or direct the movement of water and/or gas within a cover system. The most common types of nonsoil impermeable materials are bituminous materials such as asphalts and tars; polymeric membranes; and concrete and cement.

3.4.2.1 Asphalt

The most common forms for asphalt encountered as a barrier are: (1) hot-sprayed asphalt/tar membranes; (2) asphalt emulsions; (3) reinforced, sprayed

asphalt membranes; (4) asphaltic concrete; and (5) prefabricated asphalt lining. A hot-sprayed asphalt membrane consists of a relatively tough, high-viscosity, high-softening-point asphalt or tar. Usually, a hot-sprayed membrane does not contain any filler or aggregate. The asphalt or tar utilized for this purpose must be ductile enough to conform to the irregularities of the base material and to resist cracking during its service lifetime, yet strong enough to withstand the stresses imposed upon it during the construction of the overlying cover layers.

An asphalt emulsion consists of three basic components: asphalt, an emulsifying agent, and water. The emulsifying agent disperses the asphalt cement in water, creating a mixture that is stable enough for pumping, prolonged storage, and mixing. Ideally, the emulsion should break down quickly upon coming into contact with the surface to be treated, and should retain all the adhesion, durability, and water-resistance of the asphalt cement from which it was formulated. Generally, asphalt emulsions are classified according to behavior in an electrical field and according to rapidity with which the emulsion will revert to asphalt cement (coalesce). Asphalt emulsions are classified as anionic, cationic, or nonionic, depending upon which direction the positively charged particles in the emulsion move when an electric current is passed through it. Emulsions are further grouped as slow-setting (SS), medium-setting (MS), or rapid-setting (RS). The prefix "C" is added to the asphalt emulsion grade if the mixture is cationic. For example, an RS-2 emulsion is either anionic or nonionic, and a CRS-2 is cationic.

Where tensile-strength requirements exceed the strength of a sprayed-asphalt membrane (such as on steep slopes), a mat of reinforcing material is added to the membrane. This reinforcement (normally a geotextile) is placed on the ground, and the asphalt is sprayed over it. Geotextiles used for this reinforcement have included fiberglass mats, polypropylene, and polyester. The selection of the geotextile should be based on the facts that the geotextile could be exposed directly to the environment and that it must possess sufficient openings to allow asphalt penetration. Delaminations in reinforced sprayed-asphalt membranes have occurred in the past as a result of the reinforcing material's being attacked by microorganisms or by the geochemical nature of the soil, as well as of inadequate penetration of the asphalt into the reinforcement.

Asphaltic concrete is a mixture of hot asphalt cement and well-graded, high-quality aggregate, compacted to form a uniform, dense mass. The type of asphaltic concrete that would be used as an impermeable barrier layer is similar to that used for highway surface courses, with the exception of having a higher percentage of mineral filler and asphalt cement.

There are basically two types of prefabricated asphalt lining material. One is manufactured in the form of a panel or board, while the other is produced in rolls, much like roofing. The prefabricated asphalt panel is stronger and more durable than the rolled lining, but the rolled lining is more flexible and less expensive. Unlike the other two types of asphalt barriers, the seaming process for prefabricated asphalt panels must be accomplished by hand. Table 3-12 compares prefabricated asphalt lining with the other two types of asphalt barriers.

9 3 1 2 9 0 4 0 9 8 4

TABLE 3-12

ADVANTAGES/DISADVANTAGES OF VARIOUS FORMS OF ASPHALT CONSTRUCTION

Material	Advantages	Disadvantages
Hot-Sprayed Membranes:	a. Provide tight impervious barriers.	a. Requires up to 3 passes to insure integrity.
a. Asphalt	b. Good availability.	b. Special heating and storage equipment required.
	c. Can be mechanically installed.	c. More vulnerable to damage from plants and animals than asphalt concrete.
	d. Does not have extensive equipment needs.	d. The subgrade soil must be carefully prepared to remove sharp or large objects.
	e. Can penetrate tight surfaces to plug voids and open surfaces.	e. Susceptible to cracking during cold-weather installation.
	f. Very dense mixtures resist plant intrusion better.	f. Protective cover is essential.
		g. Cannot support much traffic (human or vehicular).
		h. Poor resistance to oils and organic solvents.
b. Tars	a-f. Same as for asphalt.	a-h. Same as for asphalt.
	g. Tars mix well with wet aggregate.	i. Tars are more susceptible to weathering effects than asphalts.
		j. Some tars require high temperatures.
		k. During application, vapors may burn personnel that come into contact with them.
Asphalt Emulsion	a. Does not have extensive equipment needs.	a. Extensive curing times may be required.
	b. Does not require a petroleum to make it liquid.	b. Subgrade soil requires careful preparation.
	c. Can be applied in most cases without the use of additional heat.	c. Cannot support much traffic.
	d. Has the ability to coat damp aggregate surfaces.	d. More vulnerable to plant and animal attack than asphalt concrete.
	e. There is little or no hydrocarbon emission.	e. Protective cover is essential.
	f. Can penetrate tight surfaces.	f. Poor resistance to oils and organic solvents.

(continued)

TABLE 3-12 (continued)

Material	Advantages	Disadvantages
Reinforced, Sprayed Asphalt Membranes	a. Greater fatigue (tensile) strength than unreinforced asphalt membranes.	a. Careful selection of fabric is required.
	b. May be placed on steeper slopes than nonreinforced membrane.	b. Cost is greater than nonreinforced membrane.
	c. Greater tear resistance than nonreinforced.	c. Delamination may occur from microorganisms or soil chemistry.
	d. Equipment needs are not too extensive.	d. Susceptible to cracking in cold weather installation.
		e. Protective cover is essential.
		f. More vulnerable to plant and animal attack than asphalt concrete.
		g. Only as good as the asphalt or asphalt emulsion sprayed on it.
Asphalt Concrete	a. Provides a very stable working surface from which to construct the rest of the cover	a. Requires specialized heating, storing, and construction equipment.
	b. Better resistance to attack from plant roots and burrowing animals than sprayed membranes.	b. Requires more highly skilled personnel than sprayed membranes.
	c. Will support traffic better than sprayed membranes.	c. Relatively stiffer material with regard to subsidence.
		d. Poor resistance to oils and organic solvents.
		e. Vulnerable to cracking during cold weather installation.
Prefabricated Asphalt Lining	a. Can be installed where it is difficult to operate machinery (asphalt distributors, pavers, rollers, etc.)	a. Expensive.
	b. Does not require the degree of subgrade compaction as the other types of asphalt materials.	b. Susceptible to cracking during cold weather installation.
	c. Can be manufactured under greater quality control than field constructed materials.	c. Panels are very heavy.
	d. Equipment needs are minimal.	d. Cannot withstand rapid changes in subgrade elevation.
	e. Resist tearing.	e. Seams are not usually as strong as panel material.
		f. The fabric must be chosen carefully as microorganisms may attack them.

9 3 1 2 9 0 4 0 9 8 6

For additional information on asphalt consult "Asphalt in Hydraulics" (Asphalt Institute, 1976).

3.4.2.2 Synthetic Membranes ("Geomembranes")

The use of synthetic membranes in the waste-disposal field now spans over two decades. Basically, these membranes fall within one of three categories: elastomers (rubbers), thermoplastics (plastics), and combinations of elastomers and thermoplastics. Butyl rubber, ethylene propylene rubber (ethylene propylene diene monomer, EPDM), and neoprene are the most commonly used rubbers, while polyethylene (PE), polyvinyl chloride (PVC), and chlorinated polyethylene (CPE) are commonly used plastics. Chlorosulfonated polyethylene (CSPE), a common commercial variety of which is Hypalon,* and DuPont's 3110 (no longer marketed) exhibit qualities found in both the rubbers and the plastics. Polyethylene is available as low-density (LDPE), high-density (HDPE), and linear low-density (LLDPE) polyethylenes. Table 3-13 presents these various types of polymeric membranes, their advantages and disadvantages, and general information concerning their engineering and physical characteristics.

When considering the use of a polymeric membrane to fulfill the functions of the hydraulic barrier, one must first explore the general advantages and disadvantages involved with choosing this type of barrier over asphalt, soil cement, etc. Generally, the advantages include: (1) a variety of compounds are available; (2) sheeting is produced in a factory environment; (3) polymeric membranes are flexible; and (4) they are relatively simple to install.

The disadvantages generally associated with polymeric membranes include: (1) the chemical resistance of the polymeric membrane must be obtained for each job; (2) seaming systems are material-dependent and are usually considered the weak link in a membrane; and (3) many polymeric membranes are vulnerable to attack from biotic, mechanical, and environmental sources. Attack by biotic agents may be controlled by adding biocides. Pinholes have been a problem with some membranes in the past, but recent improvements in membrane manufacture have markedly reduced the problem.

The hydraulic barrier in most cases may be underlain by other layers (e.g., gas collection and foundation), isolating it from heavy concentrations of the hazardous chemicals. However, site conditions allowing a contractor to place a membrane directly on a contaminated soil are within the realm of possibility. Even if not directly in contact with a solid contaminant, a polymeric membrane may be affected by the chemical composition of any gases intercepted in a gas-collection layer located beneath the liner. With these points in mind, consider the specific advantages and disadvantages listed above. Polymeric membranes are available in a wide variety of compounds suitable for coming in contact with various chemicals. However, no one compound is resistant to the entire spectrum of chemicals that might be encountered at an uncontrolled hazardous waste site. Also, it is highly unlikely that any one type of hazardous chemical will be encountered by itself.

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* Registered trademark of E.I. DuPont de Nemours & Co., Inc.

TABLE 3-13

COMMONLY USED POLYMERIC MEMBRANES[a]

Polymeric Membrane	Advantages	Disadvantages	Field Seaming Method	Usable Temperature Ranges (°F)	Typical Widths (ft)	Typical Lengths (ft)	Available Thickness (mils)	Reinforced Available?
Butyl Rubber	a. Longest service history	a. Poor resistance to ozone and abrasion	a. Gum tape	-50 to 200	20-35	250-500	20 to 125	Yes
	b. Good availability	b. Resistance to oils and solvents is not good	b. Vulcanization					
	c. Good heat resistance.	c. May be difficult to achieve a good quality seam in cold or wet weather	c. Contact adhesives					
	d. Low vapor transmissivity							
EPDM	a. Good weathering characteristics	a. Poor oil and hydrocarbon resistance	a. Gum tape	-50 to 200	Up to 45	100	20 to 60	Yes
	b. Good ozone resistance	b. More difficult to vulcanize than butyl	b. Vulcanization					
	c. Resists attack by dilute aqueous acids and alkalies, phosphate esters, ketones, alcohols, and glycols	c.	c. Contact adhesives					
	d. Good heat resistance							
HDPE High Density Polyethylene	a. Good ozone resistance	a. Greater degree of contraction and expansion than most polymerics may increase stresses at seams	a. Heat welding	to 140	10 to 34	200-1000	20 to 140	No
	b. Resistant over a wide range of chemicals	b. Seaming in hot environment can be difficult due to undulation of sheeting						
	c. Available in greater thicknesses than other polymeric membranes	c. Susceptible to environmental stress cracking (surface cracks)						
	d. Thicker (60 mils) membranes are more resistant to mechanical, plant, and animal damage	d. Relatively stiffer material than other polymeric membranes						
	e. Large sheet widths reduce the number of seams per given area							
CPE	a. Good ozone resistance	a. Poor resistance to solvents	a. Heat welding	to 158	to 100	200	10 to 90	Yes
	b. Can be laminated with other plastics (such as PVC or PE)	b. Problem concerning delamination between plies of this film and nylon reinforcing fabrics	b. Contact adhesives					
	c. Good resistance to burning	c. Solvent seams are not as good as heat welded seams	c. Solvent					
	d. Good UV resistance		d. Gum tapes					
	e. Good resistance to soil microorganisms							
	f. Good hydrocarbon resistance							

(continued)

[a]This information was compiled from Kays (1977), Portuss (1980), Shultz and Mikles (1982), and T.R. 113 (1979)

TABLE 3-13 (continued)

Polymeric Membrane	Advantages	Disadvantages	Field Seaming Method	Usable Temperature Ranges (°F)	Typical Widths (ft)	Typical Lengths (ft)	Available Thickness (mils)	Reinforced Available?
PVC	a. Low initial cost	a. Stiffens with age because plasticizer leaves the compound	a. Solvent	15 to 150	6	Several hundred	10 to 30	Yes
	b. Good acid resistance	b. Decrease in tear resistance with age						
	c. Good availability	c. Poor resistance to ozone						
	d. Good abrasion resistance	d. Poor resistance to UV						
	e. Relatively easy to field seam	e. Susceptible to attack by soil microorganisms						
		f. Poor resistance to oils						
		g. Difficult to bond to foreign surfaces (concrete, etc.)						
		h. Poor puncture resistance						
Hypalon	a. Good resistance to ozone, UV, and abrasion	a. Surface aging can occur if left in sun making field seaming difficult if surface core is not removed	a. Solvent	to 150	5	300 to 500	30-45	Yes
	b. Good puncture resistance	b. Low tensile strength	b. Heat welding					
	c. Good abrasion resistance	c. Shrinkage can be a problem in unreinforced membrane	c. Contact adhesives					
	d. Not adversely affected by soil chemicals or microorganisms	d. Will not withstand exposure to heavy concentrations of certain oils and solvents						
	e. Good availability							
	f. Mold resistant							
Neoprene (Chloroprene rubber)	a. Good resistance to oils, grease, gasoline, acids, and alkalies	a. More expensive than other natural and synthetic rubbers	a. Contact adhesive	-10 to 200	20	100	20 to 60	Yes
	b. Good resistance to abrasion, ozone, and UV rays	b. Cannot be seamed in cold or wet weather without protection	b. Gum tapes					
	c. Stronger joints than Butyl and EDPM are attainable	c. Requires careful compounding to resist attack by microorganisms						

Usually, conditions at a Superfund site involve a variety of chemicals over a range of concentrations. Therefore, polymeric membrane candidates should be tested with a representative mixture of chemicals and concentrations or, ideally, with actual samples from the site under study. By using actual samples from the site, the designer obtains a better understanding of the polymeric membrane's limitations, as well as establishing a degree of confidence in the use of the material.

However, the cover designer should keep testing requirements in perspective. Because the covering membrane lies above the wastes, it will not be as directly exposed to aggressive liquids as an underlying liner or a sidewall. Possible threats are capillary upward migration of liquids, which is considered unlikely, or upward migration of vapor through a pervious foundation soil, possibly followed by condensation on the underside of the membrane. Tests exposing various polymeric materials to various waste fluids have established certain incompatibilities (Haxo et al., 1980, 1983). However, all such tests were by direct exposure to liquids, and as far as is known, no testing has been done with membranes exposed to vapors. There is reason to believe (H. Haxo, Jr., personal communication, 19 May 1983) that the cover environment may be markedly less severe than that of a liner or sidewall as regards chemical attack.

A big advantage polymeric membranes have (from a materials standpoint) over barriers that are fabricated in the field (such as soil cement, asphalt concrete, soil-bentonite mixtures, etc.) is that polymerics are manufactured in a factory environment, where quality-control measures can be used that are either impossible or impractical to use in the field. However, each type of membrane is subject to its own particular set of actual or potential problems, as shown in Table 3-13.

Polymeric membranes manufactured in small widths are seamed together in the factory to form large panels. These factory seams are generally of high quality. However, for most jobs these panels must be seamed in the field. The field seam is potentially the weakest link in the integrity of the completed membrane, although high-quality seams are commonly achieved by modern seaming methods and quality-control practices. The quality of a field seam is controlled by: (1) the compatibility of the seaming system with the polymeric material; (2) the skill of the seaming crew; and (3) the ability of the seaming system to perform in adverse conditions (wet, cold, dusty, hot, etc.).

Selection of a certain membrane material may require the use of a certain seaming system, and for one reason or another a given seaming system may not be usable at a given site. Therefore the designer must be informed regarding seaming systems. As seen in Table 3-13 there is not a single seaming system that will work for every type of polymeric material. The seaming methods commonly used are: (1) adhesive/solvent systems; (2) systems using heat only; and (3) systems using heat and extrudite. Usually, the best source of information concerning the proper seaming system to use is the product's manufacturer.

Seaming with adhesives and solvents has been the most widely used method over the years. Although the words "adhesives" and "solvents" have been used

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synonymously in seaming operations, the two are separated here to address adhesive tapes separately. Adhesive tapes have been used with materials that resist solvent attack (such as butyl rubber and then polyethylene sheets). A fair amount of skill is involved with its use as the alignment of the two sheets must be very good and usually the entire length of the sheet is seamed at one time. The tape is basically a double-faced tape (sticky on both sides) which is placed along the edge of one sheet, has the protective backing removed, and then has the second sheet placed on top of it (Figure 3-16(a)). The same type of lap joint is used in a solvent seam (Figure 3-16(b)). However, the effectiveness of a solvent seam is attributed to the solvent's ability to attack the polymeric membrane making it "tacky." Solvent joints involve the application of the solvent (brush and spray applications have been used) to both sheets, overlapping, and applying pressure for a sufficient length of time (Figure 3-16(b)). With solvent seams, sufficent time must be allowed for the seam to cure before imposing any load on it. This curing time allows the bond strength to develop. A modification of the lap splice is the tongue-and-groove splice (Figure 3-16(c)), commonly used with EPDM and butyl rubber sheeting.

Heat welding systems (heat only) basically melt the sides of the membranes to be joined and follow the heat with pressure (Figure 3-17), thus creating a fusion welding of the two membranes. If properly done, this method provides a strong, high-quality seam. However, this system is very sensitive to wind, dust, cold, and rain.

The third seaming system is extrusion welding. This technique employs molten plastic (normally the same material as the polymeric membrane) and extrudes it on top of (Figure 3-18) or in between the membranes (Figure 3-19) to form a seam. This is the seaming method used in joining high-density polyethylene (HDPE).

Seams are subject to two failure modes, shear and peel (Figure 3-20), both of which must be considered when evaluating field seaming.

To date, geomembranes have been used much more as liners than as covers. The information presented in this Handbook is largely based on experience with geomembranes in liner applications. Because of their different respective positions, membranes in liner service should be more subject to attack by liquid chemicals, while those in cover service should be more vulnerable to vapors, ozone, or biotic agents.

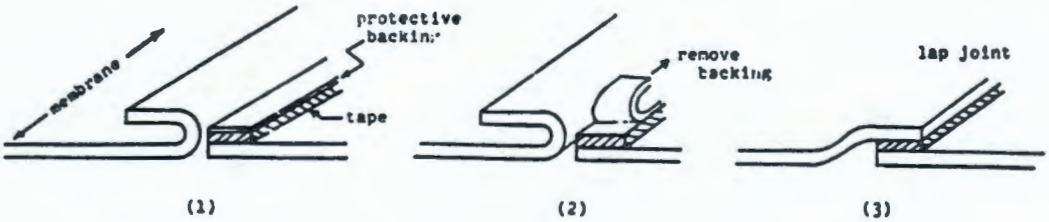
3.4.2.3 Concrete and Cement

The use of cement in a hydraulic barrier manifests itself in two areas: concrete and soil-cement.

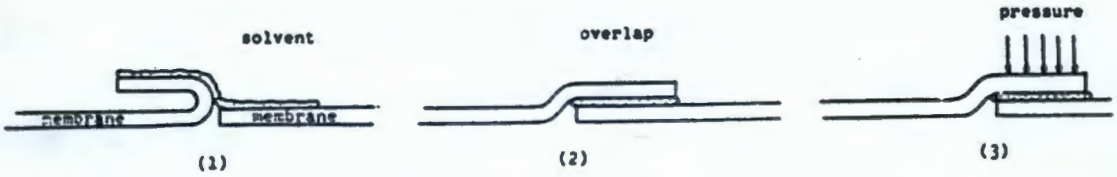
(1) Concrete. Concrete has been used in the past to line water-holding structures. However, concrete was utilized most for this purpose at a time when the engineer had a very limited selection of hydraulic-barrier materials (Kays, 1977). Problems with cracking, leakage at construction joints, costs

FIGURE 3-16

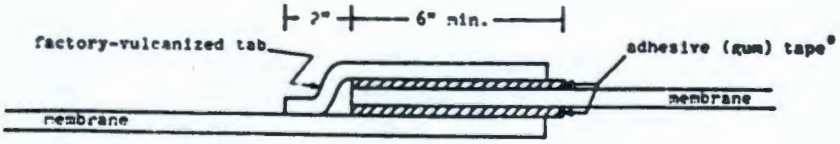
TYPICAL ADHESIVE/SOLVENT SEAMS



a. ADHESIVE (GUM) TAPE SEAM



b. SOLVENT SEAM



(Courtesy E.I. du Pont de Nemours & Co. Inc.)

* Manufacturers recommend use of both tape and solvent on both sides of joint for EPDM and butyl rubber membranes

c. TONGUE-AND-GROOVE SEAM

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FIGURE 3-17

HEAT WELDING

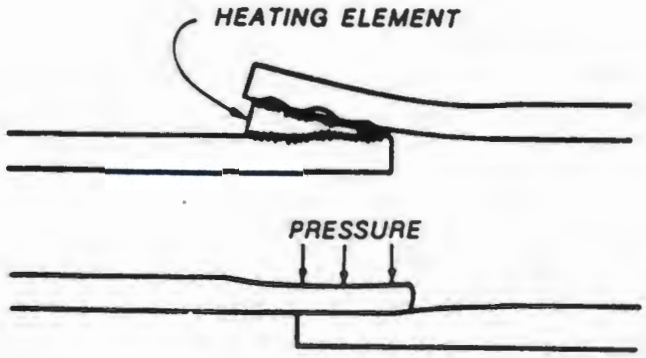


FIGURE 3-18

EXTRUSION WELDING SYSTEM - TOP-LAID

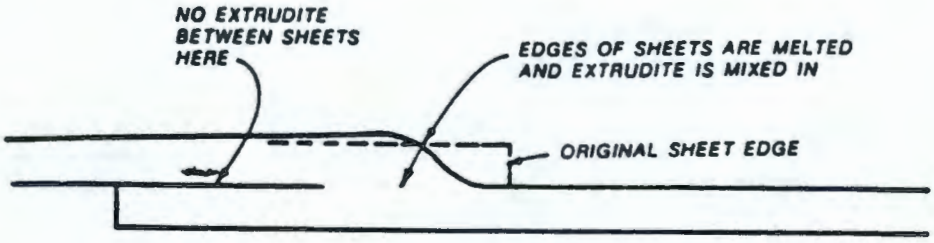
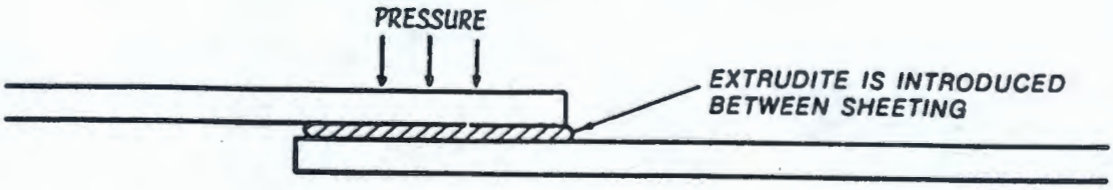


FIGURE 3-19

EXTRUSION WELDING SYSTEM - INTERMEMBRANE



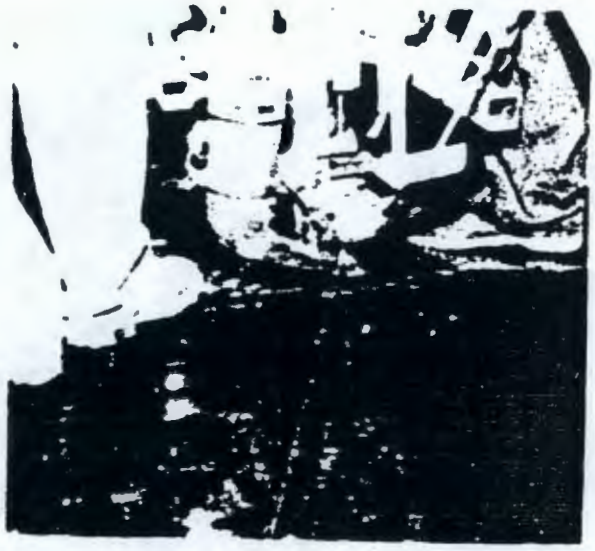
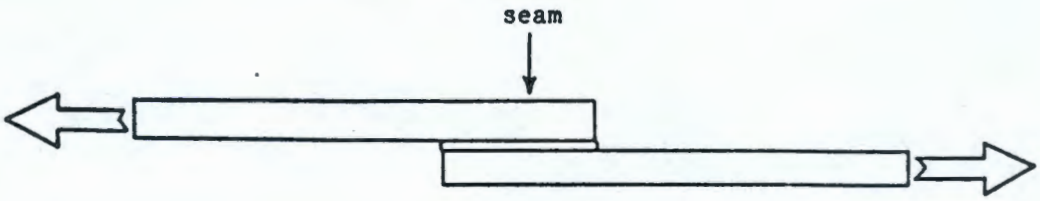
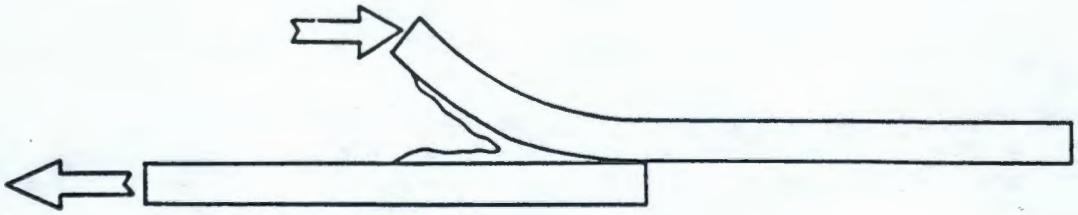


FIGURE 3-20

SEAM FAILURE MODES



a. SHEAR



b. PEEL

of labor and materials, and the advent of cheaper, more flexible materials have kept concrete from being used extensively as a hydraulic barrier in the field of waste disposal. For these reasons the discussion of concrete will be limited to this section and not included in the section on design.

The following factors are important in the design of concrete (reinforced and nonreinforced) as a hydraulic barrier (in a cover system):

- Subgrade
- Side slope
- Concrete mix
- Joints and waterstops
- Type of reinforcement (reinforced concrete only)
- Curing

9 3 1 2 9 0 4 0 9 9 9 6

In reinforced versus unreinforced concrete, there are advantages and disadvantages connected with either. Unreinforced concrete is cheaper, and is usually considered hydraulically tighter, as closer joint spacing is usually required. With smaller panels, less space will be created at joints due to contraction of the concrete. On the other hand, unreinforced concrete is highly dependent on a stable substrate and is more susceptible to cracking due to thermal effects while exposed. A good source of information on the design and testing of concrete is the US Army Corps of Engineer's "Handbook for Concrete and Cement." A discussion of concrete in construction may also be found in Backstrom et al. (1974).

(2) Soil-cement. Soil-cement is created by a process in which onsite soils, or soils imported from other areas, are mixed with portland cement and water, and compacted. Soil-cement has been used to line water impoundments and canals and to provide embankment protection for dams and shorelines. Soil-cement has found its greatest use in areas where clay or clayey soils are not found within economical distances of the site, but sandy soils are available. Because soil-cement is a relatively brittle material, careful attention must be given to the supporting substrate. Also some special consideration must be given to the bonding of lifts and to curing; these items are discussed in Chapter 4.

Soil-cement is essentially a mixture of portland cement and a sandy, usually well-graded soil (maximum aggregate size - 3/4 inch). As a general rule, any soil that can be pulverized easily and contains less than 50 percent silt and clay is suitable for soil-cement construction (Kays, 1977).

Generally there are two categories of soil-cement; compacted soil-cement and plastic soil-cement. Compacted soil-cement differs from the plastic mix in the amount of water added to the mixture. Compacted soil-cement is compacted at or near the mixture's optimum moisture content. Plastic soil-cement has a consistency like plaster or mortar, which require more water and cement than the standard mix. Although the compacted soil-cement mix is more commonly used, plastic soil-cement has been shown to be practical for small areas or where larger equipment cannot be used.

In the design and construction of a soil-cement hydraulic barrier the following criteria must be considered:

- Cement quality
- Cement content
- Optimum moisture content
- Density
- Permeability
- Effects of freeze-thaw cycles
- Effects of cycles of wetting and drying

- Compaction (field control)
- Bonding
- Curing

Table 3-14 presents some general guidance for the average cement content required for different types of soils. However, the soil-cement mixture should be designed on the basis of a laboratory testing program. Table 3-15 presents a list of design criteria and some representative laboratory tests used to acquire these parameters.

One of the parameters important to the soil-cement layer's ability to function as a hydraulic barrier is permeability. Table 3-16 gives some examples of the permeabilities of cement-treated soils. From Table 3-16 one can see that as the percent-by-volume cement content increases, the coefficient of permeability decreases for a given soil. However, cement content is not the only factor by which the permeability of soil-cement is affected. The degree of compaction plays an equally important role. A rule of thumb has been that a soil-cement layer must be compacted to at least 95 percent Standard Proctor density. However, this will be borne out or refuted in the laboratory testing program.

The nature of the fluids to which the barrier may be exposed is another matter that should be considered. Acids and alkalies may attack the cement.

Methods of constructing a soil-cement layer are described in Chapter 5, "Construction."

The cost of a soil-cement layer depends primarily on two factors, the cost of processing and the cost of cement. The cost of processing includes the costs of processing material, hauling materials to the site, water for curing and mixing, central-plant mixing, transporting the soil-cement at the site, spreading, compacting, and curing. The cost of cement includes delivery and contractor's cost. The cost of processing is somewhat quantity-dependent. The Portland Cement Association (PCA) lists approximate 1982 costs as follows:

Less than 5,000 cubic yards - $13.75/cu yd

5,000 to 10,000 cubic yards - $12.00

10,000 to 40,000 cubic yards - $10.50

40,000 to 100,000 cubic yards - $9.00

More than 100,000 cubic yards - $8.25

The PCA also states that a 6-inch layer of soil-cement costs about $0.50/square foot ($27.00/cubic yard) installed.

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TABLE 3-14

AVERAGE CEMENT REQUIREMENTS FOR EXPOSED SOIL-CEMENT SLOPE PROTECTION

Unified Soil Classification Symbol	Average Cement Content (percent by weight)
GW	7
GP	7-8
GM	8-9
GC	9
SW	7-8
SP	7-11
SM	8-12
SC	9-12
CL	12
CH	--
ML	12
MH	--

TABLE 3-15

REPRESENTATIVE LABORATORY TESTS FOR SOIL-CEMENT DESIGN PARAMETERS

Parameter	Laboratory Test Designation
Cement Quality	ASTM C150, CSA A5, AASHTO M85, ASTM C595, AASHTO M240
Cement Content	ASTM D558
Optimum Moisture Content	ASTM D559
Maximum Density	ASTM D560
Permeability	ASTM D2434
Freeze-Thaw Effects	ASTM D560
Wet-Dry Effects	ASTM D559
Soil Classification	ASTM D2487, AASHTO M145

TABLE 3-16

PERMEABILITY OF CEMENT-TREATED SOILS

Soil Number or Sample Identification	Dry Density, pcf	Moisture Content, Percent	Cement Content Percent by Volume	Type of Soil-Cement	K, Coefficient of Permeability, ft per year	USDA Texture	Gradation Analysis, Percent Passing 3/4	4	10	40	200	.05	.005	AASHTO Soil Class[a]	Cement Requirement by Volume[b]
Standard Ottawa sand	108.2	10.8	0	Compacted	48,750	Coarse sand	(100% pass #20; 0% pass #30)							A-1-b(0)	--
	112.8	9.4	5.7	Compacted	6,940										
	117.6	9.7	11.3	Compacted	76.3										
SP soil, 11 H-26 Idaho	--	--	0	Plastic	2,460	Sand	100	99	98	73	9	8	3	A-3(0)	--
	98.6	24.1	8	Plastic	130										
	99.8	20.1	8	Plastic	130										
	100.3	18.8	20	Plastic	0.8										
Graded Ottawa sand	103.2	13.7	0	Compacted	16,300	Sand	100	100	100	#50	#100	--	--	A-1-a(0)	--
	104.7	13.6	5.3	Compacted	473					28	2				
	107.4	12.3	10.3	Compacted	21.4										
PCA soil No. 7018 Florida	101.0	12.2	0	Compacted	746	Sand	100	100	100	91	7	1	--	A-3(0)	10.0
	100.9	13.3	3.1	Compacted	562										
	103.6	12.3	6.3	Compacted	192										
	105.3	12.0	9.2	Compacted	21.1										
PCA soil No. S-2 Illinois	100.8	14.9	0	Compacted	4,960	Fine sand	100	100	100	96	13	12	2	A-2-4(0)	8.0
	99.9	14.7	3.1	Compacted	1,359										
	104.0	15.1	6.3	Compacted	59.5										
	104.8	15.1	9.2	Compacted	11.5										
PCA soil No. 6998 Maine	104.8	10.6	0	Compacted	2,400	Coarse sand	100	100	96	51	5	2	--	A-3(0)	7.0
	107.2	9.5	3.3	Compacted	651										
	111.7	10.3	6.8	Compacted	36.2										
	113.4	10.2	9.9	Compacted	7.6										
PCA soil No. 6863-2 Maryland	104.9	10.3	0	Compacted	1,640	Sand	100	100	100	77	4	--	--	A-3(0)	8.5
	106.6	10.8	3.3	Compacted	90.3										
	112.4	10.3	6.8	Compacted	25.6										
	114.4	10.3	10	Compacted	3.6										
SP sand, 11 H-X65 Utah	100.1	16.0	0	Compacted	356	Fine sand	100	99	99	96	6	6	1	A-3(0)	--
	105.8	14.8	6	Compacted	19.8										
	109.3	13.5	12	Compacted	1.1										
PCA soil No. 7019 Florida	101.0	13.8	0	Compacted	144	Fine sand	100	100	100	94	2	--	--	A-3(0)	11.0
	106.7	13.3	3.1	Compacted	33										
	108.2	13.4	6.5	Compacted	0.3										
	108.8	13.4	9.5	Compacted	0.02										

[a]All soils nonplastic.

[b]Cement requirement based on ASTM Standard Freeze Thaw and Wet-Dry Tests for Soil-Cement Mixtures and PCA Paving Criteria.

Source: Portland Cement Association's Soil-Cement Information Bulletin IS173.02W

3.4.3 Permeable Materials

Permeable nonsoil materials include bulk residual or waste materials from various industries, drainage pipes and tiles, and geotechnical fabrics known as "geotextiles." Residual materials comprise both organic and inorganic wastes.

In considering any material, the designer will consider its functional suitability and cost. At any given site, a residual material may be available locally at low cost. If so, the designer must determine whether the material is suitable for cover applications. Residual materials proxy for soils, and share a good deal in common with them. Residual materials possess a gradation and various measurable bulk properties, and may be classified by the USCS. A residual material is likely to be similar to a natural soil with the same USCS group symbol, although some qualitative differences are likely.

3.4.3.1 Organic Residual Materials

Organic residual materials are generated largely by the paper and forest-products industries. .In the same way that organic soils are generally undesirable from an engineering viewpoint because of inferior mechanical properties, organic residuals are generally undesirable in the same way. Paper-mill slimes, probably the most common organic residual, are fine in size, low in density, high in water content and difficult to dry out. Sawdust and wood chips, which formerly were mostly burned, are now largely recycled within the forest-products industry. These, however, might find application in a cover system as a soil amendment to promote vegetative growth. Such use should be planned with guidance from competent agronomical experts.

3.4.3.2 Residual Materials from the Mining and Metallurgical Industries

The largest quantities of inorganic residual materials are generated in the mining and metallurgical industries. These materials include mine and pit wastes, mine mill tailings, furnace slag, and others. An extensive research program was conducted for the Federal Highway Administration on the potential use of mining wastes as highway materials, and reported in four volumes under the general title of "Availability of Mining Wastes and Their Potential for Use as Highway Material" (Collins and Miller, 1976; Collins, 1976a, 1976b; Collins and Miller, 1977). Those parts of a cover system that function as a foundation or as a subsurface drainage member have counterparts in highway construction. In addition, both highway engineers and cover designers face the problem of handling surface drainage and of preventing erosion on slopes or in channels. The above-named series of reports presents a wealth of information on mineral waste materials, including practical use experience in various highway applications and an extensive discussion of the economics of shipping bulk materials by truck, train, and barge.

In general, mineral residuals of coarse grain size are more useful than fines. Thus slags, waste rock, and the coarser fractions of various mineral tailings tend to find acceptance as materials for highway use. The fines tend to be unacceptable because, being the products of crushing and grinding of rock, they are nonplastic rock flours or silts, having little or no cohesion. Such materials are highly susceptible to erosion, highly susceptible to frost heaving where that is a problem, and lacking in surface-active properties such as cation exchange capacity, so that they are infertile. Thus fines, to some extent including fly ash (discussed below), may find applications as additives or blending media, but generally fail to find productive uses as an unaccompanied material.

3.4.3.3 Fly Ash

Fly ash (FA) is a residual material of a somewhat special character. For one thing, FA is generated in large and fairly constant quantities; for another, it has achieved acceptance as a standard construction material in the concrete industry, being the subject of three ASTM specifications (C-311, C-593, C-618). FA has received much study, research and testing, and as a material is well documented. In the context of the electric utility industry, where most FA is produced, it is a residual product requiring storage and disposition; but in other contexts it is definitely a resource and a raw material.

Most FA is formed during the combustion of pulverized coal. At the high temperatures during firing, the noncombustible mineral matter in the coal is fused into molten droplets, which on cooling congeal to form glassy spheres. Microphotographs of FA show it to be an assemblage of nearly perfect spherical particles. The specific gravity of FA is lower than most common soil minerals, averaging about 2.4, and there is reason to believe that some of the FA spheres are hollow. Chemically the FA is siliceous, aluminous, and iron-bearing, with variable lesser quantities of other oxides, mainly CaO, MgO, Na_2O, and SO_3. The percentage of silica (SiO_2) varies between about 30 and 55 pct. There is a systematic tendency for Western-US FA's to be high in lime (CaO) and for Eastern ones to be low. Because any lot of FA reflects the coal from which it was formed, the chemistry of FA's is variable.

Considered as a soil, FA is a fairly uniformly graded silt, with median size (D_{50}) ranging roughly between 20 and 40 microns. FA is extremely nonplastic, as might be expected from its spherical grain structure. As is common with silts, FA is seriously erosion-prone and frost-action-prone. As expressed by DiGioia and Nuzzo (1972), FA is "a dusty nuisance when dry and an unmanageable quagmire when saturated," but can be easily handled and compacted at intermediate water contents. For a set of Western Pennsylvania FA's, these authors indicated maximum dry densities in the Modified Proctor test (see above) ranging between 77 and 89 pcf. The densities are quite low in comparison with most soils, and reflect the low specific gravity of FA.

Most FA's are pozzolanic, and this property has been the basis of most of FA's industrial use. A pozzolan is a siliceous or siliceous-aluminous material

which, in the presence of moisture, will react with lime to form a cementitious compound. Most FA's are also distinctly alkaline.

There are obvious economic incentives to develop uses for FA. Several organizations promote established uses and the search for new ones, and there have been several research symposia, both in North America and abroad, devoted to ash utilization. A summary of applications and technology was published in 1970 by the U. S. Bureau of Mines (Capp and Spencer, 1970). The established avenues of application for FA are in the field of cement and concrete; as a light-weight aggregate in concrete and building blocks; in engineering soil stabilization; as a mineral filler in asphalt mixes; in agriculture; and in brick manufacturing. The soil-stabilization and agricultural applications may be pertinent to cover systems.

The vegetative component of a cover system may benefit from mixing of FA into the plant-supporting soil. The silty size of FA promotes a loamy soil texture, which is favorable for plant growth. FA may be a source of nutrients, and may be capable of delivering them over extended periods. Moreover, the alkalinity of FA may act as an effective neutralizer for acid soils. Seasoned ash is preferable to raw ash, as the latter may show some plant toxicity; the elements producing the toxicity are quickly leached away in the seasoning process. The cover designer is advised to consult research reports for detailed discusssions of FA's agricultural effects.

In engineering soil stabilization, FA's pozzolanic properties come into effect. Greater or lesser amounts of lime, depending on the lime content of the FA, need to be added for the stabilization reaction to occur. A careful review of such use has been published by Barenberg (1974). Materials to which LFA (lime, fly ash, aggregate) or LCFA (lime, cement, fly ash, aggregate) stabilization is appropriate are coarse-grained soils (gravels and sands) and other coarse-grained aggregates such as crushed rock and various slags. This requirement agrees in general with recommended practice in "Soil Stabilization for Pavements" (Depts. of the Army, Air Force, and Navy, 1982). Various factors are important for production of an acceptable result, including proper mix, proper compaction, and proper curing conditions and time. The result is a relatively hard, rigid material with good durability and dimensional stability. According to Barenberg (1974, pp 186-7) the stabilized material has the property of autogenous healing.

Published permeability data on FA-stabilized soil are scarce. Parker, Thornton, and Cheng (1977) reported on permeability testing of two Arkansas soils with which a Western-US fly ash with very high lime content (20.0 percent CaO) had been mixed. Only one of these soils, a SP-SM (USCS), was an appropriate type for FA stabilization; the other was an organic clay (OH), an uncommon soil. Barenberg (personal communication, 24 March 1983) reports that the stabilized material can be made quite impervious, and that k values as low as 10^{-8} cm/sec can be achieved with proper gradation and compaction.

Whether FA should be considered for use in a cover system, other than for agricultural purposes as discussed above, requires judgment on the part of the designer. Placed over an unstable, settlement-prone foundation, an FA-stabilized soil, or any stabilized soil, is threatened with cracking, an

obviously undesirable condition for prevention of percolation. If there is assurance that the wastes are reasonably stable and if a thick enough stabilized layer can be placed, strong enough to bridge minor underlying slumping, it is reasonable to expect that a durable and effective cover could be produced. There is no known actual experience to date with the use of such a design.

3.4.3.4 Other Residual Materials

Other residual materials include boiler bottom ash and slag, incinerator residues, foundry sand, plant sludges, reservoir and channel silt, dredged material, and composted sewage sludge (Lutton, Regan, and Jones, 1979). Any of these may in special circumstances be considered for cover applications. The cover designer should determine a given material's properties and, by comparison to soils or other known materials, decide whether the material can suitably be used in the cover.

3.4.3.5 Pipes and Tiles

Subsurface drainage systems have been constructed using a variety of materials. These materials have included sands and gravels; pipes of various materials (vitrified clay, concrete, steel, plastic, etc.); and geotechnical fabrics. Of these materials, sands and gravels have the longest history of use as underdrainage materials. The use of sand and gravel can be primarily attributed to their durability, low cost, and availability.

A system employing only sand and gravel has a lower drainage capacity than one that includes a system of pipes and/or drainage tiles to intercept and transport the infiltrated water to an outlet. Design and construction considerations for such a system are presented in section 4.7. The pipes and tiles used in the drainage layer should meet the strength and durability requirements imposed upon them by the site conditions as well as carry their designed flow.

Current specifications covering the quality of the materials are presented in Table 3-17. These specifications should be used as guidance in determining a product's acceptability for use in a drainage installation. However, there are some acceptable modifications to these specifications, given site-specific conditions. For example, if a clay tile will not be subjected to damage from freezing and thawing before, during, and after installation, the testing related to freeze-thaw effects can be modified or waived.

Much of the use of buried pipe and tile has been in the field of agricultural drainage. Information on this subject can be obtained from "Drainage for Agriculture" (Van Schilfgaarde, 1974). Materials and methods are particularly discussed in Fouss (1974) and Willardson (1974). Agricultural drains are also discussed in Bouwer (1978).

9 3 1 2 9 0 4 1 0 0 4

TABLE 3-17

DRAINAGE-MATERIALS SPECIFICATIONS (LEE ET AL., 1984)

	Specification
Clay drain tile	ASTM C 4
Clay drain tile, perforated	ASTM C 498
Clay pipe, perforated, standard, and extra strength	ASTM C 700
Clay pipe, testing	ASTM C 301
Concrete drain tile	ASTM C 412
Concrete pipe for irrigation or drainage	ASTM C 118
Concrete pipe or tile, determining physical properties of	ASTM C 497
Concrete sewer, storm drain, and culvert pipe	ASTM C 14
Reinforced concrete culvert, storm drain, and sewer pipe	ASTM C 76
Perforated concrete pipe	ASTM C 444
Portland cement	ASTM C 150
Asbestos-cement non-pressure sewer pipe	ASTM C 428
Asbestos-cement perforated underdrain pipe	ASTM C 508
Asbestos-cement pipe, testing	ASTM C 500
Pipe, bituminized fiber (and fittings)	Fed. Spec. SS-P-1540
Homogeneous perforated bituminized fiber pipe for general drainage	ASTM D 2311
Homogeneous perforated fiber pipe, testing	ASTM D 2314
Laminated-wall bituminized fiber perforated pipe for agricultural, land, and general drainage	ASTM D 2417
Laminated-wall bituminized fiber pipe, physical testing of	ASTM D 2315
Styrene rubber plastic drain and building sewer pipe and fittings (perforations, if needed, are specified in ASTM D 2311)	ASTM D 2852
Plastic drainage tubing, corrugated	Soil Conservation Service Specification
Pipe, corrugated (aluminum alloy)	Fed. Spec. WW-P-402
Pipe, corrugated (iron or steel, zinc coated)	Fed. Spec. WW-P-405

3.4.3.6 Geotextiles

The term "geotextile" or "geotechnical fabric" refers to an uncoated synthetic textile product that can be incorporated into an engineered structure and the uses of which do not require it to be watertight. Geotextiles usually fulfill five basic functions (or combinations thereof):

- Filtration
- Drainage
- Separation
- Reinforcement
- Armoring

Table 3-18 defines these functions more fully.

These functions can be used for a variety of practical applications. However, the designer should note that in performing its primary function, the geotextile may be performing a secondary function that the designer might exploit. Table 3-19 presents examples of some practical applications of geotextiles as well as the primary and secondary functions associated with them.

After primary and secondary functions have been established, the next step is determining the most suitable geotextile for the application at hand. An evaluation should be based on four characteristic areas:

- Constructibility
- Durability
- Mechanical characteristics
- Hydraulic characteristics

Within each area, the designer must consider a group of properties in determining a geotextile's suitability. Although these properties may vary somewhat between fabric functions, many are held in common. Table 3-20 presents these properties as they relate to the different characteristic areas (criteria for selection).

Geotechnical fabrics are manufactured from a variety of synthetics, including polypropylene, polyester, polyethylene, nylon, polyvinylidene chloride, and fiberglass. The most commonly used are polypropylene and polyester. The physical properties of all these materials can be varied considerably by varying the additives used in the manufacture and the methods of processing the filaments. Therefore, careful consideration must be given to the types of polymers present in a geotextile and the manufacturing process that produced it. Generally, the same scrutiny should be applied to geotextiles as to

9 3 1 2 9 0 4 1 0 0 6

TABLE 3-18

DESCRIPTION OF GEOTEXTILE FUNCTIONS

Function	Description
Filter	The process of allowing water to escape easily from a soil unit while retaining the soil in place. The water is carried away by some other drain (e.g., rock or rock with pipe).
Drain	The situation where the fabric itself is to carry the water away from the soil to be drained.
Separation	The process of preventing two dissimilar materials from mixing. This is distinct from the filtration function, in that it is not necessary for water to pass through the fabric.
Reinforcement	The process of adding mechanical strength to the soil-fabric system.
Armor	The process of protecting the soil from surface erosion by some tractive force. Usually in these situations, the fabric serves only for a limited time.

Source: Bell, Hicks, et al. (1980)

synthetic membranes, as regards their compatibility with substances and conditions to which they will be exposed in service.

The most commonly used method of general geotextile classification is by manufacturing process. Geotextiles are classified as woven, nonwoven, and knitted. Woven fabrics are made as the name implies. The geotextile is manufactured in a process similar to that which produces clothing material. Weaving tends to produce fabrics with relatively high tensile strengths and moduli (ratio of tensile stress to tensile strain). However, these fabrics have a relatively low elongation at rupture, and their modulus is greatly dependent upon the orientation of the fibers to the load. If the fabric is loaded on a

TABLE 3-19

APPLICATIONS AND CONTROLLING FUNCTION OF GEOTEXTILES

Primary Function	Applications	Secondary Function(s)
Filter	Trench Drains	Separation Drain
	Pipe Wrapping	Separation, Reinforcement
	Base Course Drains	Drain
	Frost Protection	
	Structural Drain	
	High Embankments	
Drainage	Retaining Walls	Reinforcement
	Vertical Drains	
	Horizontal Drains	
Erosion Control (Armor)	Culvert Outlets	Filter
	Seeding, Mulching	Filter
	Ditch Armoring	Filter
	Embankment Protection Scour	Filter
Reinforcement	Reinforcement over soft ground	Drain, Separation
	Retaining Structures	Drain, Separation
	Fill Reinforcement	
Separation	Paved Roads	Reinforcement
	Working Platform	Reinforcement
	Railroad	Reinforcement
	Aggregate Surfaced Roads	Reinforcement

Source: Adapted from Bell, Hicks, et al. (1980)

bias, a dramatic decrease in the fabric's modulus occurs (although the ultimate breaking strength may increase). Also, the manufacturing process is the most expensive.

Nonwoven fabrics are produced in a process by which continuous filaments or staple fibers are laid on a supporting screen or belt (to form a mat) and then bonded by one of the processes described below (Horz, 1983):

TABLE 3-20

IMPORTANT CRITERIA AND PROPERTIES FOR EVALUATING A GEOTEXTILE

Criterion	Property[a]
Constructibility	Fabric Strength Temperature Stability UV Light Stability Wet and Dry Stability Flammability Thickness Weight Absorption (Wet Weight) Puncture Resistance Cutting Resistance Modulus Specific Gravity Flexibility Tear Resistance Seam Strength
Durability	Ultraviolet-Light Stability Chemical Stability Biological Stability Thermal Stability Wet-and-Dry Stability Abrasion Resistance Animal, Vegetable, and Insect Resistance
Mechanical Characteristics	Tensile Strength Fatigue Seam Strength Burst Strength Puncture Resistance Tear Strength Fatigue Creep - Static Creep - Dynamic Friction/Adhesion Modulus - Static[b] Modulus - Dynamic[b]
Hydraulic Action	Thickness Permeability Siphoning Capacity Pumping Resistance Piping Resistance Intrusion Resistance Clogging Resistance

[a]All may not be important for every application

[b]Applicable to reinforcement function only

Source: Adapted from Bell, Hicks, et al. (1980)

- Needle punching. Bonding by needle punching involves pushing many barbed needles through the fiber mat normal to the plane of the fabric. The process causes the fibers to be mechanically entangled. The resulting fabric has the appearance of a felt mat. The size of the needles determines the sizes of the largest openings in the fabric, but the complex structure of the matted filaments determines the overall permeability and pore characteristics. Needle-punched fabrics can be formed by needling a single mat thickness or by needling several mat thicknesses together.

- Heat bonding. In this process the mat is laid and then the fibers are bonded at some or all of the points where fibers cross one another. This can be done by incorporating fibers of the same polymer type but having different melting points in the mat or by using heterofilaments, that is, fibers composed of one type of polymer on the inside and covered or sheathed with a polymer having a lower melting point. With heterofilament bonding, up to 100 percent of the fiber crossover points can be bonded, the number of bonds being controlled by the percentage of heterofilaments in the mat.

- Resin bonding. Resin is introduced into the fiber mat, coating the fibers and bonding the contacts between fibers.

- Combination bonding. Sometimes a combination of bonding techniques is used to facilitate manufacture or confer desired properties. Since needle punching tends to leave the fibers relatively free to move with respect to each other, heat or resin bonding can be combined with it to increase the dimensional stability of the fabric. Very open woven fabrics are also sometimes coated to fix filament positions.

Combination fabrics are fabrics which combine two or more of the fabrication techniques previously described. The most common combination fabric is a nonwoven mat that has been bonded by needle punching to a woven scrim. The nonwoven mat may be on one or both sides of the woven backing.

The knitting process is not a commonly used manufacturing process. In fact, only two fabrics are known to be made by this process (Horz, 1983). One is employed in surface erosion protection, while the other is used for unidirectional soil reinforcement. The advantages of the knitting process are that the strength properties can be varied unidirectionally or multidirectionally, it is possible to knit tube shapes, and the process is less expensive than weaving.

Table 3-21 presents general guidance as to the types of geotextiles that have been applied in various practical uses.

TABLE 3-21

GEOTEXTILES USED FOR VARIOUS PRACTICAL APPLICATIONS

USE	FABRIC
Drain Filter	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film and Monofilament Woven
Separation: Light Duty	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film Woven
Separation: Heavy Duty	Mediumweight Bonded and Mediumweight Needled Nonwoven and Slit Film Woven
Reinforcement: Light Duty	Monofilament and Slit Film Woven and Heavy Needled Nonwoven
Reinforcement: Heavy Duty	Multifilament Woven
Erosion Conrol: Light Duty	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film and Monofilament Woven
Erosion Control: Medium Duty	Slit Film and Monofilament Woven and Mediumweight Bonded and Mediumweight Needled Nonwoven
Erosion Control: Heavy Duty	Very Heavyweight Needled Nonwoven, Heavyweight Woven, and Special Heavyweight Combination Woven-Nonwoven Fabrics
Silt Fences	Lightweight Bonded and Lightweight Needled Nonwoven and Slit Film Woven
Drainage	Heavyweight Needled Nonwoven

Source: Bell, Hicks, et al. (1980)

CHAPTER 4

DESIGN OF A COVER SYSTEM

4.1 Introduction

4.1.1 Basic Considerations

In designing a cover system, three basic issues must be considered:

- Design life of cover system
- Primary function of cover
- Future use

The term "design life" refers to the span of time during which the cover system (all of its elements) will perform as expected. This time requirement will be one of the primary motivators as to the types of materials that can be used, as well as the overall design philosophy. For instance, if installing a cover over an uncontrolled hazardous waste site is all that is to be done, then the "design life," for all intents and purposes, may well be considered indefinite. On the other hand, if the cover is installed in conjunction with a system that will ultimately render the site safe within a finite period (such as leachate recovery and treatment program), then the cover design should reflect this. However, beyond a certain length of time the terms permanent and temporary become arbitrary. Generally, if an engineered product is expected to last for more than 50 years it is considered permanent. Therefore, the cover-system designer is faced with the decision of either using a material that will last the "design life" of the cover system or designing a system that allows those elements that will not last the design life to be replaced without affecting the cover's efficiency. An example of this can be seen in the choice of a material to act as a hydraulic barrier in a cover system with a design life of 30 years. Given site-specific conditions, the designer may choose a material such as a clay which could normally be expected to last the entire "design life" of the cover (if not disrupted by vegetation). The designer might also elect to use a polymeric material with the stipulation that it be replaced or a reinstallation made over the old cover system within the required lifetime of the cover. The normal lifespan of most polymeric membranes is generally considered to be 20 years, but this is uncertain, because few field installations of membranes have been in place this long. One may note that Government regulations as well as financial considerations

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(such as estimating future costs with the degree of confidence necessary) normally act as an incentive toward using materials that will last the design life of the cover system.

A factor that ties in closely to the "design life" concept is the function that the cover is designed to fulfill, whether it should function as a "leaky roof" or as a "watertight roof." The type of roof will depend on the decision as to how much water will be allowed to percolate through the site. If the function of the cover is to reduce the flow of contaminants leaving a site to some acceptable level, then the cover's design should reflect this. If the cover system is expected to intercept <u>any</u> water percolating toward the waste, then the designer must choose a system and materials that will meet that end with a required degree of confidence.

In considering the future use of a site, the designer, along with the regulatory agency, should consider whether the public will ever have access to the site. This is an important question from the standpoint that many normal land-use activities (farming, installing septic tanks, basements and water wells, etc.) will penetrate the cover system and violate its integrity. These land uses may also place the public in close proximity to where the waste was placed. This raises a question in the basic philosophy of the design of the cover system. If the cover system (in conjunction with the remedial action as a whole) will serve to isolate or encapsulate the waste and the future use of the site includes access to the public, then will the waste still be potentially harmful when and if the cover is penetrated? This question relates to the choice of the cover system's primary function (leaky or watertight). A watertight cover is essentially futile unless the public is unequivocally denied access during the design life of the system. Although the question of future use may have been decided before the designer is involved, it is an important overall consideration. Moreover, if it is not resolved, the cover designer might be blamed in the future for a failure that was not under his control.

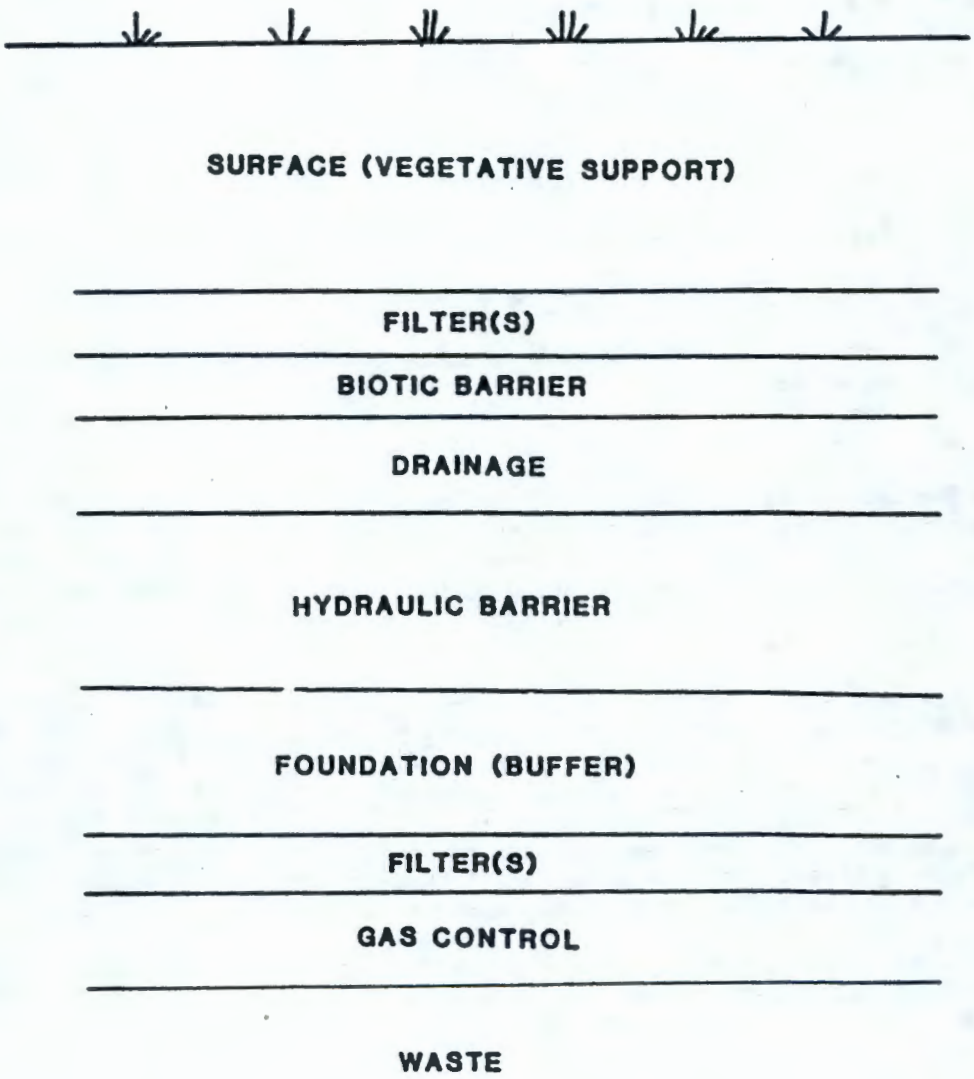
One of the greatest challenges facing a cover system may be maintenance, over the long term, of both an intact, impervious hydraulic barrier and a stable vegetative community at the surface. The natural tendency of vegetation is to establish itself in diverse communities, with some species projecting their roots downward, seeking water from deeper levels than others. In the process, the roots not only break up the soil, but tend to penetrate any barrier that stands in their way. The long-term stability of membranes, either synthetic or of clay, exposed to root attack is undemonstrated.

4.1.2 Structure of a Cover System

Figure 4-1 presents a schematic of the elements that may be found in a multilayered cover system. Not all elements may be required for any given site, but it is likely that cases will exist where all of the cover elements are required. Which elements are needed will be determined on a site-specific basis.

FIGURE 4-1

STRUCTURE OF A COVER SYSTEM



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The uppermost layer is called the surface or vegetative layer. Its primary requirements are to:

- Provide for vegetative growth
- Minimize wind and rain erosion
- Resist cracking
- Resist freeze-thaw deterioration
- Preserve slope stability
- Provide protection from the elements for the layers below it
- Provide a compatible host material for the site's surface water management program
- Provide an aesthetically pleasing appearance

The second layer shown is a filter layer. Its function is to prevent migration of fine particles in the surface layer into the coarser-grained layer immediately below. Filter layers are required whenever materials of strongly contrasting gradation are placed adjacent to one another and groundwater percolation is possible. A filter layer may or may not be needed in a given cover system.

The next layer's purpose is to resist the intrusion of plant roots and burrowing animals. Although the presently most feasible method of controlling penetration of plant roots lies in the careful selection of short-rooted grasses, research is underway by various facilities (Los Alamos National Laboratory, Pacific Northwest Laboratories, Illinois State Geological Survey, etc.) on utilizing other methods such as sand, gravel, and cobble mixtures and pelletized herbicides to prevent root intrusion into underlying wastes. Research aimed at defeating burrowing animals has also been pursued.

Underlying the biotic barrier is the drainage layer, whose function is to intercept water that percolates through the upper layers and divert it to a collection and disposal system.

The next layer is the hydraulic barrier, whose primary function is to prevent or impede the passage of any downward-percolating water that comes into contact with it. Together, the barrier and drainage layers perform the primary function of a roof: intercepting the downward flow of water and disposing of it safely.

Underlying all of the previously mentioned cover layers is the foundation layer, which provides a stable working surface from which to construct the rest of the cover system. It is essential to recognize that, up to this point, none of the cover elements is intended to act as a structural entity. In other words, the upper cover elements are not intended to hold the cover system together; rather their integrity depends on the stability of the

substrate beneath them. The foundation layer may provide part of this support, but it cannot be relied on as a subsidence preventative. The foundation layer should be considered as providing a working and supporting surface; but any massive subsidence such as that generated by the collapse of waste packages or soil bridges between packages, or cavities in the soil or rock beneath the wastes, should be handled in a stabilization program (which is not included in the scope of cover design).

Between the foundation layer and the wastes may be incorporated a gas-control layer to intercept any gases that may evolve in the wastes and, by proper venting, relieve any pressure from these gases that might build up behind the hydraulic barrier. If need be, a filter layer may be required as shown.

At the base of the system, of course, lie the wastes themselves, and any temporary covering soil that may have been placed in the past.

4.1.3 Design Procedure

Figure 4-2 presents a flow diagram outlining a general approach to the problem of preparing a cover-system design. Figure 4-3 presents a flow chart for review of potential problems. Every site requires a site-specific design. Therefore, the initial point of reference should be any site-characterization/site-exploration work accomplished, as discussed in Chapter 2. From the site's specific characteristics, an idea can be gained of the demands that the site will impose on the cover system. With these demands in mind, the designer can establish how the cover system must function to produce the desired end result (watertight or leaky roof; if leaky, how much leakage is acceptable). Then, the cover elements are chosen to fulfill these functions. For each element, a variety of materials (with their related installation practices) may be used. These general methods and materials are evaluated according to their suitability to perform the element's required functions under the imposed conditions, their availability in the vicinity of the waste site, and their cost. This evaluation will create a list of suitable materials for each cover element, ranked relative to one another. By taking the most suitable material for each element, a preliminary "preferred" cover design can be formulated. This preliminary cover design is evaluated as to the compatibility of the different construction operations involved with each element's selected material or materials. This evaluation will insure that the construction practices involved with the installation of one element will not adversely affect the performance of any other cover element. If a conflict exists that cannot be resolved by modification of the material or the construction process, then the next most suitable material for that element (or elements) should be evaluated. The end result of these series of selections and evaluations is a cover system whose design, construction, and operational qualities have all been taken into consideration.

The next section, "Infiltration and Percolation," discusses the water balance operating at a cover system. In the sections that follow, cover elements are treated in order from the bottom up (cf. Figure 4-1). The last

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FIGURE 4-2

GENERAL DECISION FLOWSHEET FOR COVER DESIGN FORMULATION

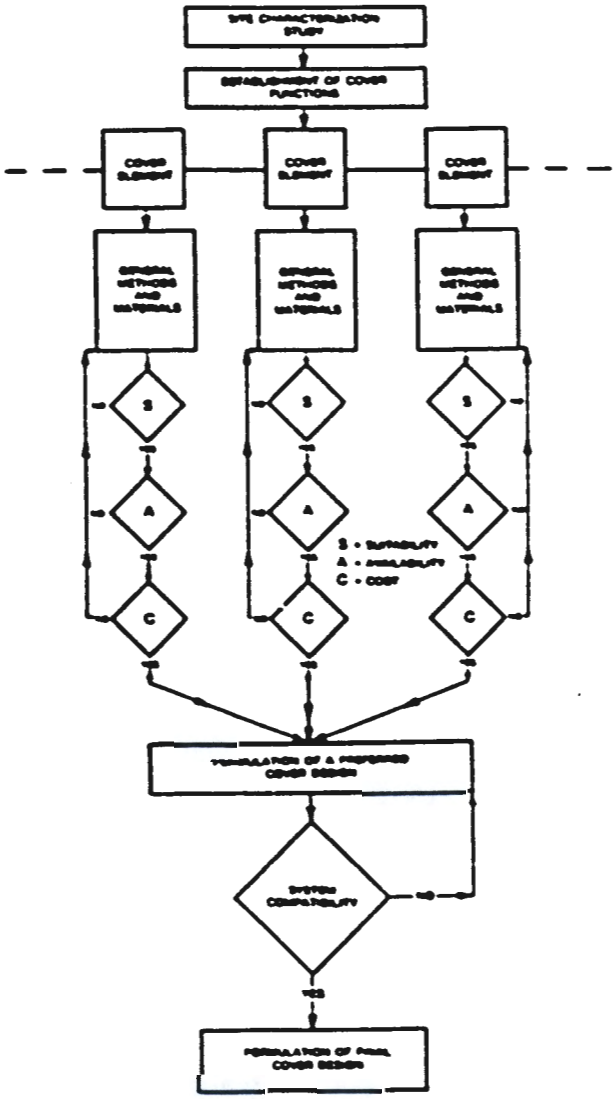
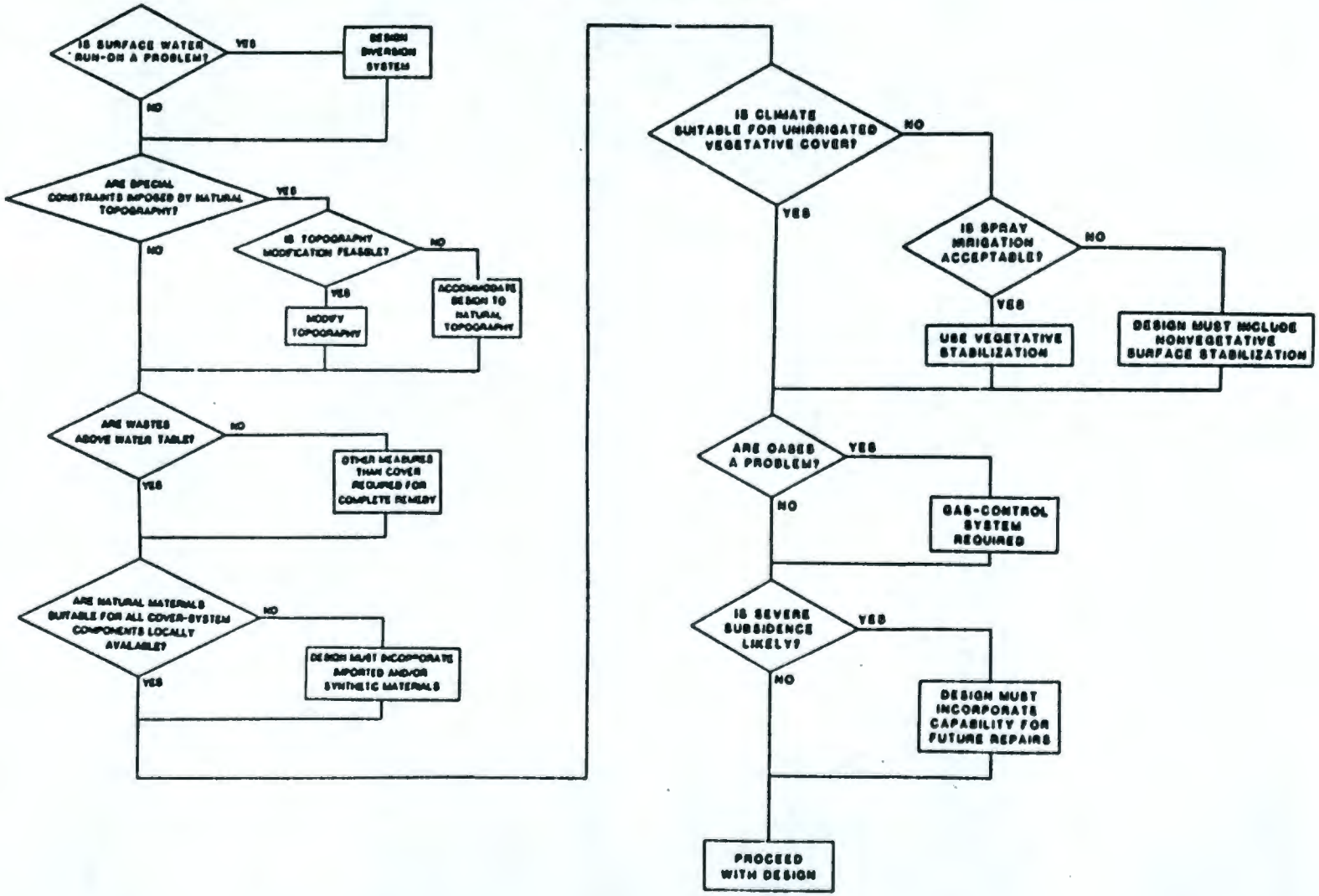


FIGURE 4-3

REVIEW OF POTENTIAL PROBLEMS



element treated will be the surface water management plan. In some respects this is the most critical element in the cover system, because it is surface water that the whole system is designed to control, and a good surface water management system minimizes the load placed on other parts of the system. The designer should keep the surface water management problem in mind as he designs the other elements of the cover system.

4.2 Infiltration and Percolation; The Water Balance

A key step in the design of a hazardous-waste-site cover system is estimating the potential amount of leachate that may be produced. To make an enlightened estimate, it is necessary to understand how water may enter the cover, move through it into the waste cells, and ultimately exit as leachate. In this section, some of the processes involved in leachate generation are discussed, and methods for estimating the volumes of leachate that may be produced are presented.

This discussion is a more detailed treatment of the subjects mentioned under "hydrologic cycle" in Chapter 1. For a clear discussion of the principles involved, the reader is referred to Bouwer (1978).

4.2.1 General Water Movement Patterns in Waste Site Areas

Water movement patterns in the vicinity of a hazardous-waste disposal site are governed by the same principles that control subsurface water flow in general. For example, consider the simplified soil/water profile presented in Figure 4-4. In the situation depicted, which is typical for most of the land mass of the earth, subsurface water may be considered to be distributed between two major regions; the zone of aeration and the zone of saturation. The zone of aeration may be further subdivided into the soil-water, intermediate (vadose), and capillary zones.

In the saturated zone, all voids are completely filled with water and, therefore, the soil moisture content, on a volumetric basis, is equal to the soil porosity. However, in the zone of aeration, some of the void space is filled with air almost all the time. Exceptions occur as moisture moves downward from the surface toward the saturated zone; for example, following a period of rain. The two principal zones are separated by a phreatic surface, or water table as it is commonly called (see Figure 4-4).

Water from precipitation or surface runon (e.g., irrigation) may enter the top of the soil column in response to capillary and gravitational forces. This process is called infiltration. However, once water begins to move through the soil, the term percolation is used to described its motion. While infiltration and percolation are conceptually different, it is difficult to separate them precisely.

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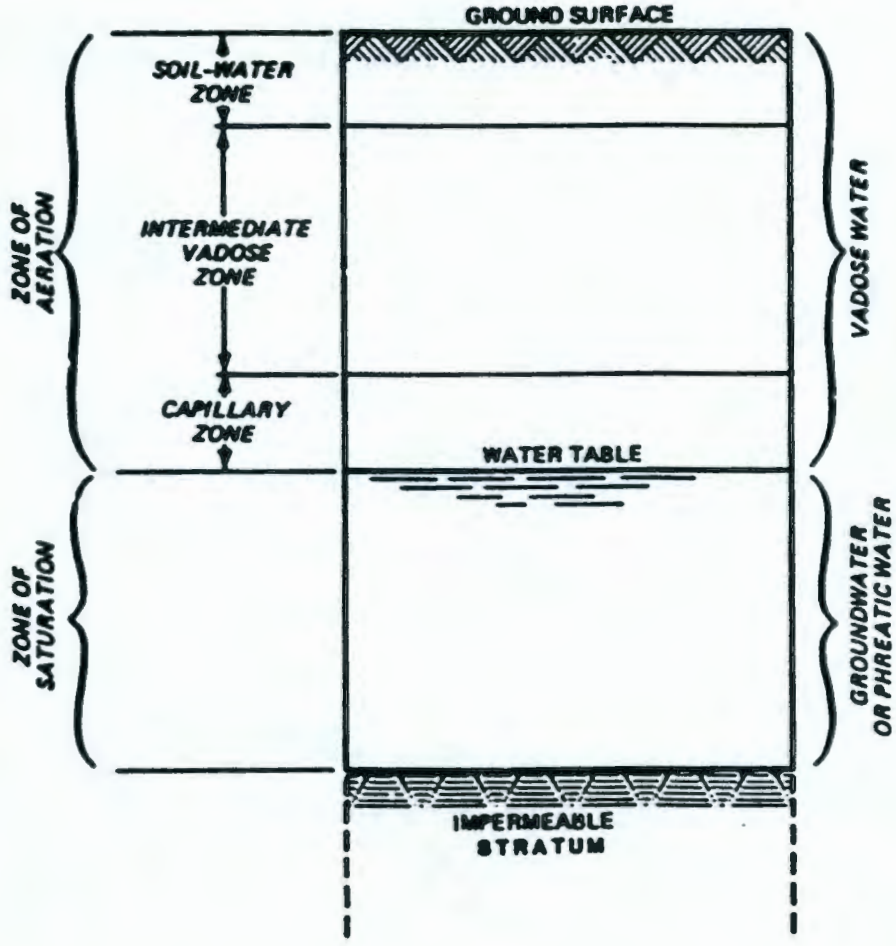
FIGURE 4-4

SIMPLIFIED SOIL/WATER PROFILE



As water infiltrates into the soil, it first enters what is shown on Figure 4-4 as the soil-water zone. The thickness of this zone varies with soil type and vegetation, but may generally be considered to extend from the soil surface down through the major root zone, that is, the depth to which major roots penetrate. In agricultural situations, the root zone may be 3 to 4 ft thick, or even greater in some cases. However, the design of most cover systems limits the root zone considerably.

If the water content of a soil is less than the field capacity, water is held stationary by a combination of capillary and electrochemical forces, and drainage (i.e., downward percolation), for the most part, cannot occur. If the soil water content exceeds the field capacity, water will move deeper into the soil column in response to gravitational forces. Agronomists generally

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define field capacity as the soil water content in equilibrium with a soil suction of one-third of an atmosphere. Soil suction refers to the tension existing in soil water under unsaturated conditions; it is a complex effect resulting from capillarity, adsorption, osmosis, etc.

As long as the water content of a soil exceeds the wilting point, plants can extract water from the soil. However, at lower water content, they remain in a permanently wilted condition. Agronomists usually define wilting point as the soil water condition at a soil suction of 15 atmospheres. The difference in the actual soil water content (limited by the field capacity) and the soil water content corresponding to the wilting point is called plant-available water because it is available to sustain vegetation. Soil water in excess of the field capacity is called gravitational water, because it may be expected to percolate under the influence of gravity. Soil water content less than the wilting point is called unavailable water, because it is tightly held and can neither percolate nor be extracted by plants.

The various relationships among the categories of soil water described above are shown graphically in Figure 4-5. Typical values for porosity, field capacity, and wilting point, along with other data to be described later, are presented in Table 4-1. (See the caution in section 3.2.6 against use of tabulated property values for design purposes.) For comparison purposes,

FIGURE 4-5

TYPICAL SOIL-WATER RELATIONSHIPS

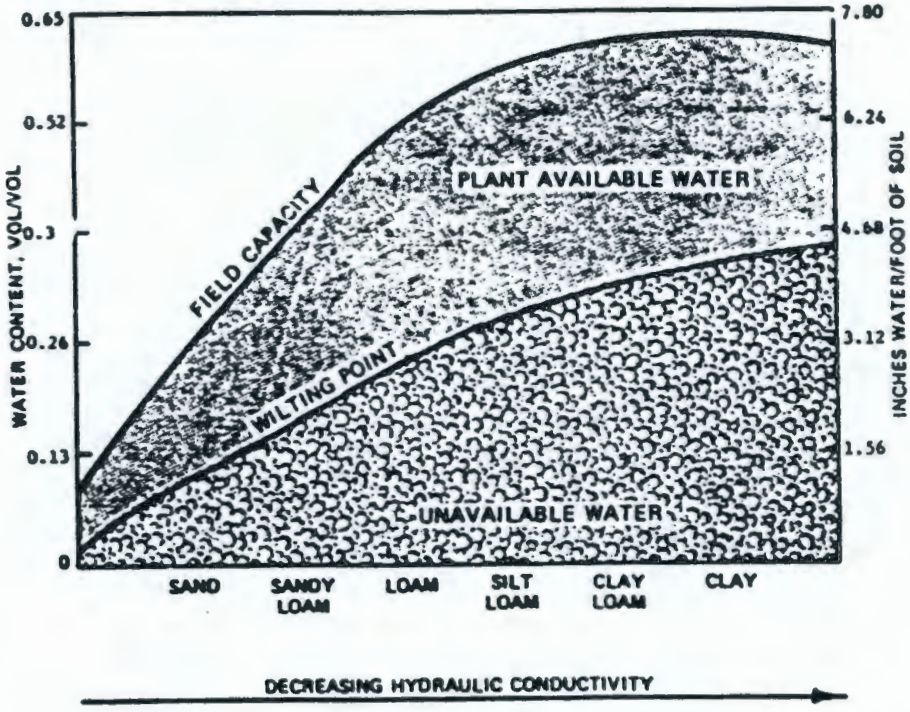

TABLE 4-1

TYPICAL SOIL CHARACTERISTICS

Soil Texture Class			MIR[d]	Porosity	Field Capacity	Wilting Point	Hydraulic[e] Conductivity	CON[f]
HELP[a]	USDA[b]	USCS[c]	In/Hr	Vol/Vol	Vol/Vol	Vol/Vol	In/Hr	$mm/day^{0.5}$
1	CoS	GW	0.500	0.351	0.174	0.107	11.95	3.3
2	CoSL	GP	0.450	0.376	0.218	0.131	7.090	3.3
3	S	SW	0.400	0.389	0.199	0.066	6.620	3.3
4	FS	SM	0.390	0.371	0.172	0.050	5.400	3.3
5	LS	SM	0.380	0.430	0.16	0.060	2.780	3.4
6	LFS	SM	0.340	0.401	0.129	0.075	1.000	3.3
7	LVFS	SM	0.320	0.421	0.176	0.090	0.910	3.4
8	SL	SM	0.300	0.442	0.256	0.133	0.670	3.8
9	FSL	SM	0.250	0.458	0.223	0.092	0.550	4.5
10	VFSL	MH	0.250	0.511	0.301	0.184	0.330	5.0
11	L	ML	0.200	0.521	0.377	0.221	0.210	4.5
12	SIL	ML	0.170	0.535	0.421	0.222	0.110	5.0
13	SCL	SC	0.110	0.453	0.319	0.200	0.084	4.7
14	CL	CL	0.090	0.582	0.452	0.325	0.065	3.9
15	SICL	CL	0.070	0.588	0.504	0.355	0.041	4.2
16	SC	CH	0.060	0.572	0.456	0.37	0.065	3.6
17	SIC	CH	0.020	0.592	0.501	0.378	0.033	3.8
18	C	CH	0.010	0.680	0.607	0.492	0.022	3.5

[a]Soil Classification system used in the HELP model (see discussion in text).

[b]Soil Classification system used by the U. S. Department of Agriculture.

[c]The Unified Soil Classification System.

[d]MIR = Minimum Infiltration Rate.

[e]Some hydraulic-conductivity values may appear high for respective USCS classes because tilled agricultural soils were considered in HELP model development.

[f]CON = Evaporation Coefficient.

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porosity and the various measures of soil water are usually expressed, in soil-science usage, in volume per volume terms. For example, if voids account for 40 percent of the volume of a given soil, the porosity may be reported as 0.4. Occasionally, it is useful to report soil water values in terms of inches. For example, consider a 24-in.-thick layer of soil having a water content of 0.50 and a field capacity of 0.45, both expressed in volume per volume terms. For this case, the total gravitational water in the soil layer is 1.2 in. That is,

total gravitational water = (soil moisture content - field capacity) (layer thickness)

or, total gravitational water = (0.50-0.45) (24) = 1.2 in.

Depending upon the amount of water that infiltrates, the rate at which water is removed by plants and evaporation, and the previous soil water content, water may percolate through the zone of aeration to the saturated zone. The capillary zone represents a transition from the saturated zone to the zone of aeration that results because water rises in the smaller (capillary) interconnected pores in response to surface-tension effects. The thickness of the capillary zone varies inversely with the pore size of the soil, and may range from only a few millimeters for fine gravel to hundreds or even thousands of millimeters for finer-grained soils.

Within the saturated zone, water movement may generally be described by Darcy's Law. One commonly used form is

$$Q/A = V = -K dh/dl \qquad (4.1)$$

where

Q = the volumetric flow rate (L^3/T),
A = the gross area through which flow occurs (L^2),
V = the "Darcy velocity" (L/T),
K = the hydraulic conductivity (L/T),
dh/dL = the hydraulic gradient (L/L).

The negative sign indicates that water flows in the direction of a decreasing hydraulic gradient. The gross area A through which flow occurs is defined more specifically as the total area, of both pores and solid soil particles, projected on a plane normal to the direction of flow. Since water cannot actually flow through the solids, it is obvious that the "Darcy velocity" does not represent the actual speed with which flow moves. The relation between Darcy or superficial velocity and actual seepage velocity is discussed in section 3.2.4.7, "Permeability."

Darcy's Law was originally developed for slow flow through coarse-grained soils. Darcy's Law is widely used in ground-water studies, since most ground-water flow is laminar. However, for dense clay soils and low hydraulic gradients, Darcy's Law may predict more flow than actually occurs. The principal reason is that electrochemical interactions between clay particles and water contained in very small pores result in nonlinearities in the relationship between flow rate and hydraulic gradient. Flow rates predicted for clay soils

and low hydraulic gradients are low anyway, and any deviations due to this effect are in the direction of even lower flows. Thus treatment by Darcy's Law is conservative from the standpoint of the cover designer.

Permeability has been discussed at length in Chapter 3. Intrinsic permeability is solely a function of the medium through which flow occurs, while hydraulic conductivity (or coefficient of permeability) is a function of both the medium and the specific fluid, water. The two measures of permeability are related as follows:

$$k = (K)\ (\mu)/(\rho)\ (g) \tag{4.2}$$

where

k = the intrinsic permeability (L^2),
K = the hydraulic conductivity (L/T),
μ = the kinematic viscosity of the fluid (M/LT),
ρ = the density of the fluid (M/L^3),
g = the gravitational constant (L/T^2)

Both intrinsic permeability and hydraulic conductivity depend upon physical factors including porosity and particle size, distribution, shape, and packing arrangement. In general, for unconsolidated media, both k and K increase with increasing particle size. Conversion factors among common units of permeability may be found in Table 3-5.

Most engineering-oriented groundwater-hydrology textbooks and handbooks concentrate on flow in the zone of saturation. It is desirable that a site be situated well above the water table, and most hazardous-waste disposal sites should be so situated that the waste, and certainly the cover system, are within the zone of aeration. (If the cover system is not within the zone of aeration, the site has severe problems, among which cover is relatively minor.) Unsaturated flow is more complex than saturated flow and is more difficult to define and describe mathematically. Much of the literature concerning unsaturated flow has been published by soil scientists, especially those interested in irrigation and plant uptake of water.

For sites that are near the water table or are subject to flooding, remedial measures other than cover will be required.

Darcy's Law can be applied to flow in the unsaturated zone. However, difficulty arises because the unsaturated hydraulic conductivity, K_u, is a function of both the soil moisture content and the soil suction. In unsaturated flow, part of the pore space is occupied by air, thus the area through which water can flow is reduced. As a result, K_u is always less than the corresponding saturated hydraulic conductivity, K. The relationship between K and K_u can be approximated mathematically as:

$$\frac{K_u}{K} = \left(\frac{S_s - S_o}{1 - S_o}\right)^3 \tag{4.3}$$

where

K_u = the unsaturated hydraulic conductivity (L/T),
K = the saturated hydraulic conductivity (L/T),
S_s = the actual degree of saturation (L^3/L^3),
S_o = the threshold degree of saturation (L^3/L^3), (that is, that fraction of pore space occupied by nonmoving water held in place by capillary forces).

This relationship may be seen graphically in Figure 3-14.

4.2.2 Cover as a Leaky Roof

The principal objective of placing a cover system over a hazardous-waste disposal site is to limit the amount of leachate that will be produced as water infiltrates and percolates downward through the site. In this discussion, any water that contacts the wastes is considered to be leachate. However, unless an impermeable (usually synthetic) membrane is used, the cover system will not be completely impermeable. Therefore, the cover system may be thought of as a sort of "leaky roof" over the disposal area. A typical three-layer system is shown schematically in Figure 4-6. The flow predictions that form the rest of this section are based on this general leaky-roof model.

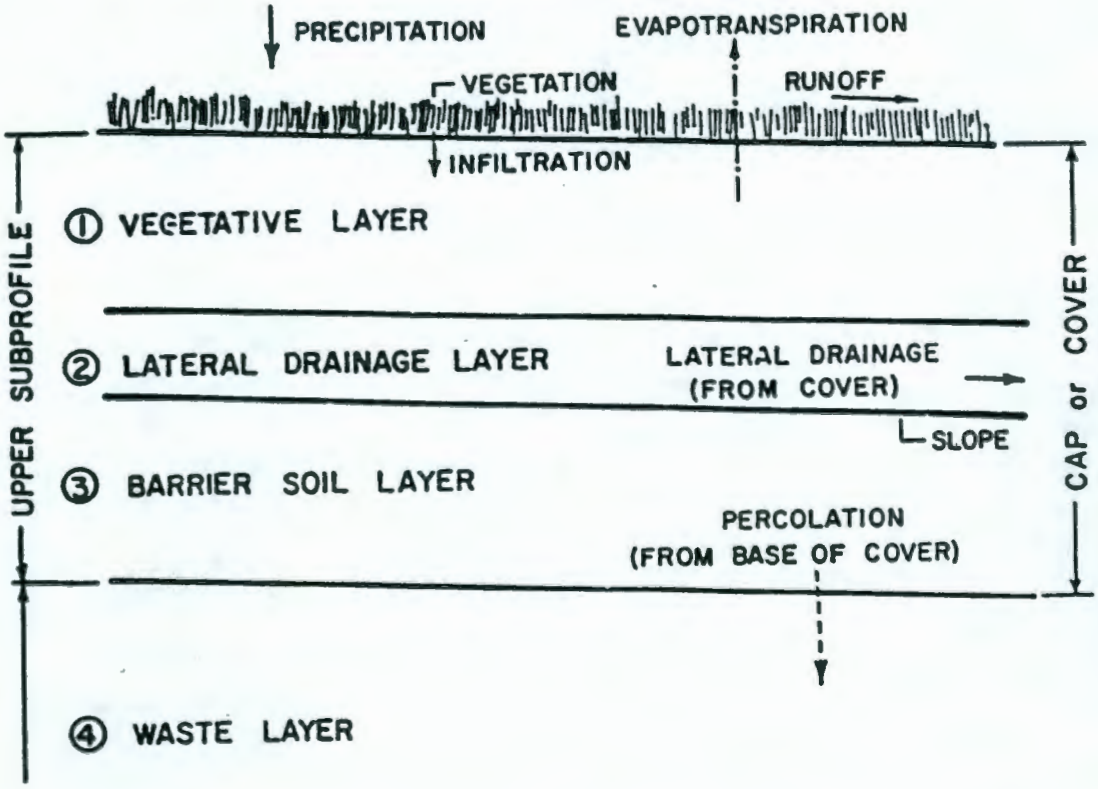
From a conceptual viewpoint, it is rather easy to write a mass balance for the flow of water onto, across, and through a cover system. Such a statement is often called a water balance. The major components of the water balance for a hazardous waste site cover are presented on Figure 4-6. As shown, precipitation falling on the site may be partitioned among runoff, infiltration, and surface evaporation (a component of evapotranspiration). Surface runon is not considered herein because good design practice calls for surface grading to prevent its occurrence. For the system illustrated, water that infiltrates the cover may be further partitioned among soil evaporation and plant transpiration (both are components of evapotranspiration), lateral drainage, soil moisture storage, and percolation downward out of the cover. This last component enters the waste cells and, thus, represents eventual leachate production. That is, this water is unlikely to be removed by any process other than continued percolation through the waste cells. For a particular site, the fate of water that infiltrates is controlled primarily by the soil moisture content. Other factors such as temperature, vegetation type, the vegetative growth cycle, etc., are also important. Unfortunately, actually constructing a detailed water balance is more difficult than grasping the concept, since some of the components are difficult to quantify. Nevertheless, virtually all methods of estimating potential leachate production depend upon water-balance calculations.

4.2.3 Precipitation

Since cover systems for hazardous-waste disposal sites are normally located well above the local ground-water table and are graded so as virtually

FIGURE 4-6

SCHEMATIC THREE-LAYER COVER SYSTEM



to eliminate surface runon, precipitation falling directly onto the site is the principal source of moisture for any infiltration and percolation that may occur. While precipitation may occur in several forms, only rain and snow are considered. Rain is by far the most important for most locations in the temperate zone.

Because of the relatively small size of hazardous-waste disposal areas, the complicated techniques often used to generate weighted-average precipitation data for larger watersheds are generally not needed. Therefore, in most cases, historical data for a nearby location will be satisfactory. However, it may also be of interest to consider hypothetical data corresponding to wet periods having known return periods.

Snowmelt may be estimated by a variety of methods (Chow, 1964). For example, the expression shown below (Soil Conservation Service, 1974) may be used to estimate the maximum snowmelt that may occur on a given day.

$$SM = 0.06\ (T - 32) \qquad (4.4)$$

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where

SM = the maximum snowmelt for the day (inches of water),
T = the mean air temperature for the day (°F).

The above expression may be used to estimate the actual snowmelt only when $T \geq 32°F$ (otherwise melting is assumed not to occur) and when the total accumulated snowpack is equivalent to (or greater than) 0.06 (T - 32) inches of water (otherwise all accumulated snow is assumed to melt). Snowmelt may be partitioned into runoff and infiltration using the same techniques discussed for rainfall in a subsequent section.

4.2.4 Runoff

4.2.4.1 General

As indicated on Figure 4-6 and discussed above, infiltration and runoff are important and closely related components of the water balance. In fact, it is not possible to estimate either one without at least an implicit consideration of the other. In this section, some methods that may be used to estimate runoff (and hence infiltration) from precipitation data are briefly discussed. A somewhat more detailed discussion of the actual process of infiltration, and the various factors that influence it, is presented below.

It is reasonable to view hazardous-waste disposal sites as very small watersheds. As rain falls (or snow melts) on such an area, some is intercepted by vegetative (or other) surfaces that may be present, and, assuming that the infiltration capacity is exceeded, puddles form in surface depressions. The scale of these depressions may vary over a wide range depending upon the nature of the cover-system surface. If precipitation (or snowmelt) continues long and hard enough, the capacity of surface depressions is exceeded and runoff begins. In the typical case, this runoff is directed to a surface drainage system and conveyed away from the site.

Selection of the runoff-estimation method best suited for a given application is influenced by a number of factors. These include the size and nature of the watershed; the precision required; the amount, quality, and type of data available; and the use that is to be made of the estimate. For example, to determine whether the yield of a watershed is sufficient to meet the long-term water-supply needs of a municipality, an estimate of the average annual runoff may be sufficient. On the other hand, to size a culvert, it is necessary to know the peak rate at which runoff will be produced for the design storm event. For hazardous-waste-site cover systems, both average and peak runoff rates may be important.

Runoff-estimation methods for design of cover systems should be applicable to very small watersheds, be relatively simple and straightforward to use, and have minimal data requirements. The data requirement is especially important since it is obvious that detailed rainfall/runoff data cannot possibly exist

for cover systems yet to be designed and built. Two conventional runoff-estimation methods that more or less meet these criteria are discussed below.

4.2.4.2 Runoff Coefficients

Runoff can be estimated directly from precipitation data if reliable runoff coefficients are available. The best-known runoff-coefficient technique is the so-called rational method. It is presented here because, for very small watersheds, it can be used with reasonable accuracy even when little site-specific data is available.

4.2.4.3 The Rational Method

The basic mathematical expression for the rational method is

$$Q = (C)\ (I)\ (A) \tag{4.5}$$

where

- Q = the runoff volume (cubic feet per second),
- C = the runoff coefficient (assumed dimensionless),
- I = the average rainfall intensity (inches per hour),
- A = the watershed area (acres).

The runoff coefficient is considered dimensionless because 1 acre-inch per hour is equal to 1.008 cubic feet per second. The principal use of the rational method is estimation of peak runoff rates for small watersheds (smaller than one square mile), especially for culvert and storm-sewer design.

The basic premise of the rational method is that the peak runoff resulting from steady, uniformly intense precipitation will occur when the entire watershed upstream of the design location just begins to contribute to the flow. This condition is met at some elapsed time, t_c, after precipitation begins; t_c is called the time of concentration. It is usually assumed to equal the time for water to flow from the most distant point in the watershed to the design location and is normally estimated from consideration of the hydraulic characteristics of the watershed. One expression that has been suggested (Kirpich, 1940) for small agricultural watersheds is

$$t_c = \frac{(7.8 \times 10^{-3})(L)^{0.77}}{S^{0.385}} \tag{4.6}$$

where

- t = time of concentration (minutes),
- L = distance from design location to furthest point in watershed (feet),
- S = average slope of watershed along distance L (dimensionless).

Once the time of concentration is known, an average rainfall intensity can be selected and the peak runoff rate can be estimated. Rainfall intensity-duration-frequency curves developed for various areas of the country (U. S. Weather Bureau, 1955) are generally used to estimate the average rainfall intensity. Guidance for selection of runoff coefficients is presented in many textbooks and handbooks. Typical values are shown in Tables 4-2 and 4-3. The values presented in Table 4-2 are most directly applicable to storms with 5- to 10-year recurrence intervals. A principal criticism of the rational method as it is commonly used is that the runoff coefficient is assumed to be constant, while it actually varies with both infiltration and precipitation. To circumvent this problem to some extent, runoff coefficients may be adjusted downwards to account for the effects of more frequent storms or storms occurring after long dry periods, and may be adjusted upwards for less frequent storms or storms occurring during prolonged wet periods. Excellent discussions of the rational method are presented by Chow (1964), Viessman et al. (1977), and Schaake, Geyer, and Knapp (1967). The Federal Aviation Agency (1970) has presented graphical procedures for estimating overland flow times.

The rational method as described above may be used directly to estimate peak runoff and, thus, make it possible to size runoff control features, such as inlets, catch basins, open channels, detention basins, and drainage pipes, for a storm of any desired recurrence interval. However, runoff coefficients may also be used to estimate daily, weekly, monthly. etc., runoff from corresponding precipitation data. For example, consider the expression shown below.

$$R = (C)\ (P) \tag{4.7}$$

where

R = total runoff for the period considered in same units as precipitation,
C = dimensionless runoff coefficient,
P = total precipitation for the period considered in same units as runoff.

Obviously, this expression suffers from the same limitations as the rational method. However, it may be used to predict runoff with sufficient accuracy to construct, for example, a monthly water balance, if care is used in adjusting the runoff coefficient to account for the relatively smaller fraction of precipitation that will run off during relatively dry periods, or in response to low-intensity rainfall (that is, it may be reasonable to assume that only precipitation in excess of some given amount will run off).

Other methods utilizing runoff coefficients are discussed by Linsley and Frazini (1979), Chow (1964), Lisley, Kohler, and Paulhus (1958), and Viessman et al. (1977). Synthetic-hydrograph methods are very popular and may be used to predict runoff from specific storms. However, since their use is usually not justified for very small homogeneous watersheds such as cover systems, they are not discussed here.

TABLE 4-2

TYPICAL RUNOFF COEFFICIENTS

Description of Area	Runoff Coefficients
Business	
Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential	
Single-family areas	0.30-0.50
Multiunits, detached	0.40-0.60
Multiunits, attached	0.60-0.75
Residential (suburban)	0.25-0.40
Apartment dwelling areas	0.50-0.70
Industrial	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30
Streets	
Asphaltic	0.70-0.95
Concrete	0.80-0.95
Brick	0.70-0.85
Drives and walks	0.75-0.85
Roofs	0.75-0.95
Lawns; Sandy Soil:	
Flat, 2%	0.05-0.10
Average, 2-7%	0.10-0.15
Steep, 7%	0.15-0.20
Lawns; Heavy Soil:	
Flat, 2%	0.13-0.17
Average, 2-7%	0.18-0.22
Steep, 7%	0.25-0.35

From American Society of Civil Engineers (1969)

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TABLE 4-3

RUNOFF COEFFICIENTS FOR AGRICULTURAL LANDS

Soil type	Watershed cover		
	Cultivated	Pasture	Woodlands
With above-average infiltration rates; usually sandy or gravelly	0.20	0.15	0.10
With average infiltration rates; no clay pans; loams and similar soils	0.40	0.35	0.30
With below-average infiltration rates; heavy clay soils or soils with a clay pan near the surface; shallow soils above impervious rock	0.50	0.45	0.40

4.2.4.4 The SCS Curve Number Method

The United States Soil Conservation Service (SCS) must frequently make runoff estimates for small watersheds where little or no precipitation/runoff data are available, but soil types, topography, vegetative cover, agricultural practices, etc., are fairly well defined. Over the years, this agency has developed a runoff-estimation technique for this kind of situation that is generally known as the SCS curve-number method. This technique is well suited to estimating runoff from cover systems. A companion method, also developed by the SCS, may be used to synthesize a hydrograph for a design storm, if such is desirable (Soil Conservation Service, 1974).

The SCS curve-number method is based upon the following empirical expression.

$$Q = \frac{[P - (0.2)(S)]^2}{P + (0.8)(S)} \tag{4.8}$$

where

Q = runoff for the time period considered (L),
P = precipitation for the time period considered (L),
S = the potential retention (L).

The retention parameter, S, may be thought of as the potential infiltration when precipitation begins. It is a function of the hydrologic properties of the soil and vegetation. S is considered to be a constant for a given storm. The so-called "curve number," CN, is actually merely a transformation of S selected to make plotting easier, and has no other physical significance. The relationship between S and CN is given by

$$CN = \frac{1000}{S + 10} \tag{4.9}$$

where

CN = the curve number (dimensionless),
S = the potential retention (inches).

By combining equations (4.8) and (4.9), it is possible to estimate runoff directly from rainfall if the appropriate value of CN can be established.

Data from many small watersheds suggests the following empirical relationship, which is implicit in equation (4.8).

$$I_a = 0.2\ (S) \tag{4.10}$$

where

I_a = the initial abstraction, i.e., all rainfall that occurs before runoff begins (L).

The potential retention, S (and thus the curve number), is related to the soil moisture content when rainfall begins. For convenience, SCS has defined three general antecedent moisture conditions: I, II, and III. These are defined as follows, in terms of the total 5-day antecedent rainfall P_{AS} (Soil Conservation Service, 1974): condition I, P_{AS} < 1.4 in. (growing season) or < 0.5 in. (dormant season); condition II, P_{AS} 1.4 - 2.1 in. (growing season) or 0.5-1.1 in. (dormant season); condition III, P_{AS} > 2.1 in. (growing season) or > 1.1 in. (dormant season). Antecedent moisture condition I represents generally dry conditions (soil moisture content above the wilting point, however) such that the soil may be plowed or cultivated satisfactorily; condition II represents "average" conditions; and condition III represents very wet (i.e., essentially saturated) soil conditions.

S (and also CN) is also a function of the hydrologic properties of the soil(s) at the site. For convenience, soils are classified as belonging to hydrologic group A, B, C, or D. The characteristics of each group are summarized in Table 4-4. Major soils of the United States and Puerto Rico have been classified by hydrologic soil group. Extensive lists are presented by Chow (1964) and the Soil Conservation Service (1974).

Another factor that affects S and CN is referred to as the "cover." In this context, the term "cover" is used to describe any material (usually vegetation) that covers the soil and provides protection from the impact of rainfall. The hydrologic condition of the cover is especially important and is generally described as poor, fair, or good. Poor conditions result from row crops, small grains, and fallow conditions. Good conditions arise from vegetative covers such as close-seeded legumes or grasses that enhance infiltration capacity. Detailed guidance for describing hydrologic condition is presented by the SCS (1974) and Chow (1964).

Two final factors that affect S and CN are land treatment practice and land use. Since the method was originally developed for agricultural areas, land treatment practices such as straight row or contour plowing and terracing

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TABLE 4-4

CLASSIFICATION OF SOILS BY HYDROLOGIC CHARACTERISTICS

Hydrologic Soil Group	Rate of Water Transmission	Rate of Infiltration[a]	Runoff Potential	General Description
A	High	High	Low	Consisting chiefly of deep, well to excessively drained sands or gravels.
B	Moderate	Moderate	Intermediate	Consisting chiefly of moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.
C	Slow	Slow	Intermediate	Consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture.
D	Very Slow	Very Slow	High	Consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material.

[a]When thoroughly wetted.

are usually considered. Land use is generally defined with respect to the type of vegetation that predominates.

Curve numbers representative of various combinations of hydrologic soil group, hydrologic condition of the cover, land use, and land treatment practice are presented in Table 4-5. The values shown are for antecedent soil moisture condition II, and assume that initial abstraction is adequately estimated by equation (4.10). Curve numbers appropriate for any antecedent moisture condition can be estimated from Table 4-6, if the curve number for any other antecedent moisture condition is known. The relationship between rainfall and runoff for various values of CN is shown on Figure 4-7. To use this figure to estimate runoff, one merely enters along the abscissa with the total amount of precipitation for the time period, reads up to the appropriate curve, and over to the estimated runoff on the ordinate.

4.2.5 Infiltration

4.2.5.1 General

Infiltration is the process by which water enters at the surface of a soil column. Any cover system other than one with a rather impervious member at the ground surface (comparable to an asphalt-surfaced parking lot) will experience infiltration. Whether the infiltrated water goes on to produce percolation depends on the design of the cover system, and particularly on the impervious-barrier member. Infiltration is a key component in any water-balance analysis. Thus it is important for the cover system designer to have an appreciation for the nature of the infiltration process, the factors that

TABLE 4-5

RUNOFF CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITION II
(ASSUMING $I_a = (0.2)(S)$)

Land Use	Cover Treatment or Practice	Hydrologic Condition	Hydrologic Soil Group A	B	C	D
Fallow	Straight row	--	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contour ' and terraced	Poor	61	72	79	82
	Contoured and erraced	Good	59	70	78	81
Close-seeded Legumes[a] or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		--	59	74	82	86
Roads (dirt)[b]		--	72	82	87	89
(hard surface)[b]		--	74	84	90	92

[a]Close-drilled or broadcast.

[b]Including right-of-way.

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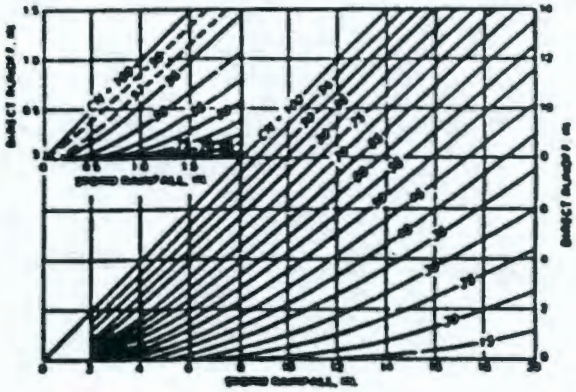
TABLE 4-6

CORRESPONDING CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITIONS I, II, AND III

CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITIONS		
I	II	III
100	100	100
87	95	98
78	90	96
70	85	94
63	80	91
57	75	88
51	70	85
45	65	82
40	60	78
35	55	74
31	50	70
26	45	65
22	40	60
18	35	55
15	30	50
12	25	43
9	20	27
6	15	30
4	10	22
2	5	13

FIGURE 4-7

RUNOFF VS. RAINFALL FOR VARIOUS SCS CURVE NUMBERS (CHOW, 1964; SOIL CONSERVATION SERVICE, 1974)



affect infiltration, and how the amount of water that will infiltrate under various design configurations can be estimated. Each of these topics is considered in the following discussion.

Over the past several years the infiltration process has been the subject of a considerable amount of both theoretical and applied research. Unfortunately, the process is so complex, and is influenced by so many factors, that no universally acceptable means of describing infiltration has yet been developed. The principal thrust of theoretical research has been to formulate partial differential equations for saturated and unsaturated flow through porous media and to develop general solutions for these equations. On the other hand, much research effort has been expended in observing the actual infiltration process under various conditions, and then attempting to describe it by means of specific empirical relationships. At present, it would appear that empirical descriptions are more suitable for estimating infiltration at hazardous waste disposal sites than are the potentially more rigorous theoretical approaches. However, in most cases, the use of an indirect means is the best approach to estimating infiltration. That is, infiltration can be estimated simply as the difference between the amount of water available at the surface of a soil column (the sum of precipitation, snowmelt and runon) and the sum of the amounts that run off and are lost via surface evaporation.

4.2.5.2 Infiltration Velocity, Infiltration Capacity, and Infiltration Rate

The <u>infiltration velocity</u> is the time rate at which water actually enters at the surface of a soil column at any given time. The <u>infiltration rate</u>, also called the <u>infiltration capacity</u>, is the maximum rate at which infiltration can occur in a given situation under specified conditions. The <u>equilibrium infiltration capacity</u> is the infiltration capacity that can be sustained over a long period of time during which the infiltration velocity is not limited by the supply of water available at the surface of the soil column. The infiltration capacity of a given soil can and does vary with time during a given storm, as discussed below.

4.2.5.3 Factors Affecting Infiltration

The infiltration velocity is controlled or limited in one of three ways. First, of course, it cannot exceed the rate at which water is supplied to the surface of the soil column. Second, it cannot exceed the rate at which water can enter the soil column. Finally, it cannot exceed the rate at which water can percolate through the soil column. Thus, any factors that affect the supply rate, the entry rate, or the percolation rate may affect the overall infiltration process.

Partitioning between infiltration and runoff is influenced strongly by the nature of the soil, and importantly also by the slope of the surface and the nature and quality of the vegetative cover. Infiltration is promoted by

9 3 1 2 9 0 4 1 0 3 6

coarse-grained soil, by flat ground, and by a well-developed vegetative covering. Runoff is promoted by fine-grained soil, by sloping ground, and by absence or sparsity of vegetation. It would seem desirable to minimize percolation in advance by minimizing infiltration and maximizing runoff, and indeed, with qualifications, this is true. However, the conditions that favor runoff also promote erosion, which is a threat to the cover once constructed and which must itself be minimized and controlled. Cover design, thus, largely involves trade-offs, of which control of infiltration versus control of erosion is one of the most important.

During part of the year at northern sites, the ground is frozen. During this period there is little or no infiltration. Either precipitation falls as snow, in which case the water remains above the ground surface until the time of thaw, or should temperatures warm to the point of permitting rain, as the water infiltrates, it will exchange heat with the ice dispersed in the soil and either the infiltrated water will freeze or the soil ice will thaw. If the former, percolation will be delayed; if the latter, percolation will proceed. Quite different processes may take place, as temperatures vary within a narrow range.

4.2.5.4 Modeling the Infiltration Process

The infiltration process was studied in detail by Horton (1933, 1939) during the 1930's. He suggested the expression shown below, which has served as the basis for the work of many other researchers.

$$f = f_c + (f_o - f_c)e^{-kt} \qquad (4.11)$$

where

- f = the infiltration capacity (L/T) at a given time, t (T),
- f_c = the equilibrium infiltration capacity (L/T),
- f_o = the initial infiltration capacity (L/T),
- k = a decay constant indicating that infiltration capacity decreases with time during a precipitation event (L/T).

This empirically derived expression reflects numerous observations that, for most soils, infiltration capacity decreases exponentially with time, so long as water is supplied to the soil surface at a rate exceeding the equilibrium infiltration capacity. A definition sketch corresponding to equation (4.11) is presented on Figure 4-8. The curves shown on Figure 4-9 are, however, somewhat more indicative of what usually happens. Curve number 1 represents a situation in which the soil profile is never saturated because the rate at which water is supplied to the surface is always less than the equilibrium infiltration capacity. If such a case no runoff occurs. Curves 2, 3, and 4 represent responses to increasing rates of supply, all of which exceed the equilibrium infiltration capacity. In each case there is a period during which virtually all the water supplied to the surface infiltrates. However, once the soil surface is saturated (indicated by t_{sat}) the infiltration rate decreases gradually until it approaches the equilibrium infiltration capacity.

FIGURE 4-8

IDEALIZED RELATIONSHIP BETWEEN INFILTRATION CAPACITY AND TIME

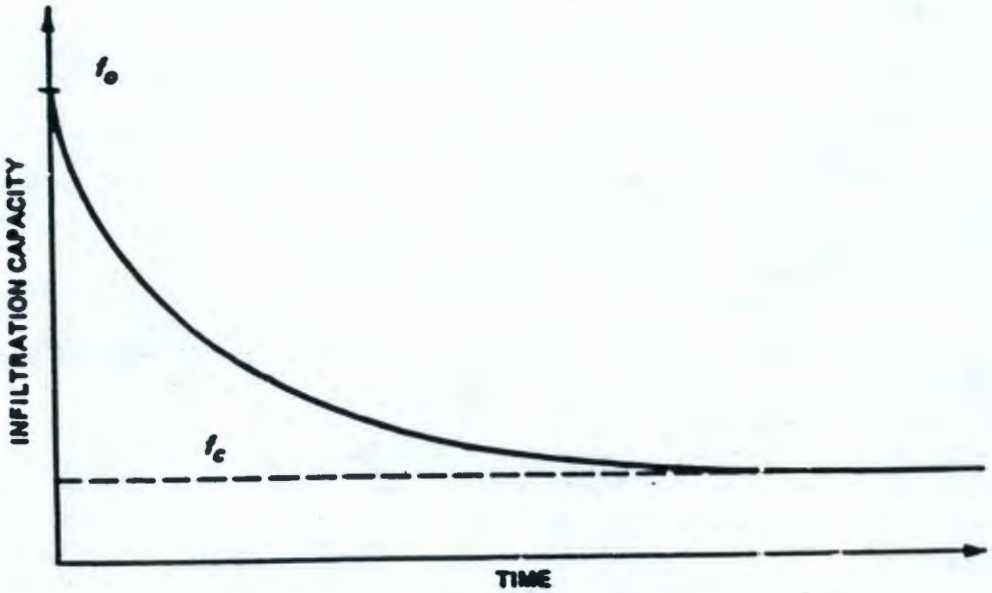
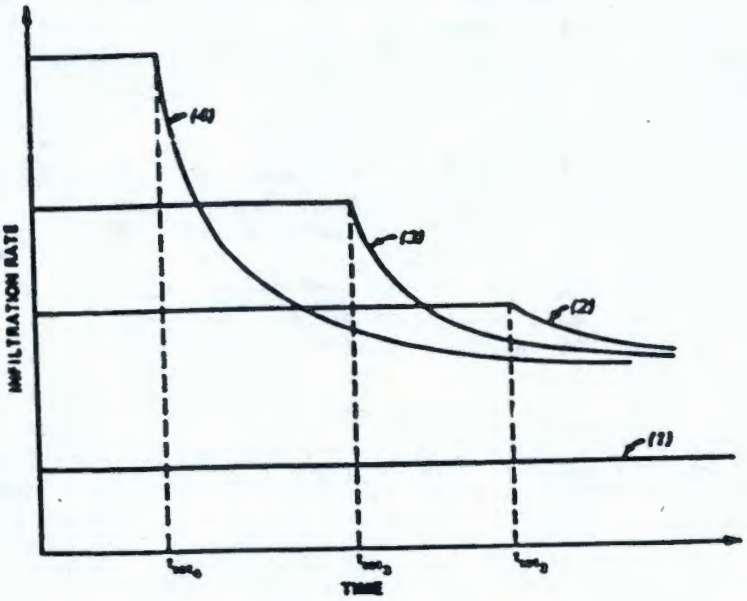


FIGURE 4-9

RELATIONSHIP BETWEEN INFILTRATION RATE AND TIME FOR VARIOUS RATES OF WATER SUPPLY



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In theory, equation (4.11) may be used to describe infiltration only after the soil surface becomes saturated and so long as the surface water supply rate exceeds the equilibrium infiltration capacity. These limitations may be circumvented by considering the infiltration rate to be a function of soil moisture content rather than time. For example, Holtan (1961) and Overton (1964) have suggested the following expression.

$$f = f_c + A\,(S - F)^P \tag{4.12}$$

where

f = infiltration capacity,
f_c = equilibrium infiltration capacity,
S = available soil moisture storage capacity (i.e., porosity minus antecedent soil moisture content),
F = total water infiltrated,
A = a numerical coefficient,
P = a numerical exponent.

Huggins and Monke (1970) have suggested the following rearrangement of equation (4.12). In this form dimensional consistency is maintained and A and P are subject to physical interpretation.

$$f = f_c + A\left[\frac{S - F}{T_p}\right]^P \tag{4.13}$$

where

T_p = total soil porosity (L),

and other variables are defined as above. With this arrangement, A may be seen to have the same units as f and f_c, and may be interpreted as the maximum potential increase in the infiltration capacity above the equilibrium value. P, which is dimensionless, is related to the rate of decrease of infiltration capacity with increasing soil moisture content. Because the value in the brackets cannot exceed unity, larger values of P must be associated with more rapid rates of decrease in infiltration capacity.

Equation (4.13) can be used only if S, F, and T_p are determined for a layer of soil having a definite thickness, usually called the control depth. The control depth may be either the depth to a soil layer that significantly impedes percolation (i.e., controls the percolation rate), or the depth at which the hydraulic gradient approaches unity. Even though it may be difficult to select a suitable control depth, an expression such as equation (4.13) is preferable to one like equation (4.11) because it is applicable even when the surface water supply rate is less than the equilibrium infiltration capacity. Thus, equation (4.13) can be used to predict the recovery of infiltration capacity that occurs during such periods.

Holtan et al. (1975) have presented a somewhat different form of equation 12 that expresses infiltration capacity as a function of predictable factors.

$$f = f_c + (GI)\,(a)\,(S)^{1.4} \tag{4.14}$$

where

f = infiltration capacity (inches/hour),
f_c = equilibrium infiltration capacity (inches/hour),
GI = vegetation growth index (percent of plant maturity),
a = vegetation parameter related to surface-connected porosity and plant root density (inch/inch^4),
S = available soil moisture storage (inches).

Specific values for GI and a for various types of vegetation are presented in Holtan et al. (1975). Typical ranges for f_c are 0.3 to 0.45, 0.15 to 0.30, 0.05 to 0.15, and 0 to 0.05 inches/hour for hydrologic soil types A, B, C, and D, respectively (see Table 4-4).

A number of infiltration models have been developed by assuming that a distinct boundary (wetting front) moves through the soil column as infiltration and percolation occur. The wetting front concept is illustrated on Figure 4-10. If the surface water supply is represented by a pool of water of negligible depth, Darcy's Law may be applied to yield an expression such as that shown below.

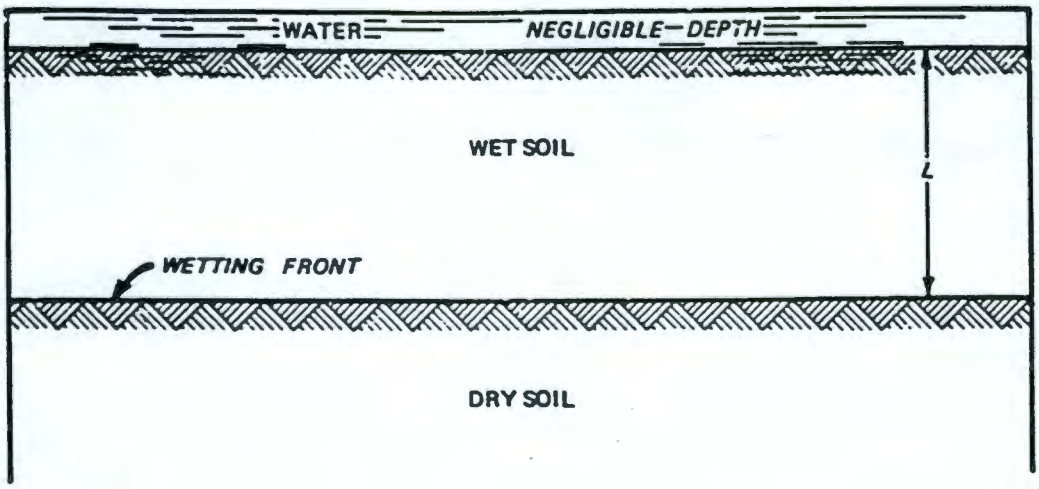
$$f = K_S \frac{L + S}{L} \tag{4.15}$$

where

f = infiltration capacity (L/T),
K_S = saturated hydraulic conductivity (L/T),
L = distance from soil surface to the wetting front (L),
S = capillary suction at the wetting front (L).

FIGURE 4-10

SOIL PROFILE AS INFILTRATION OCCURS



This expression, reported by Green and Ampt (1911), has served as the basis for several infiltration models which have appeared in the literature in recent years. The principal difficulty with such a model is predicting the capillary suction.

The American Society of Civil Engineers (1949) has presented a simple empirical technique for estimating infiltration. The key to the method is the infiltration capacity one hour after excess precipitation (i.e., precipitation at a rate greater than the equilibrium infiltration capacity) begins. This infiltration rate, given the symbol f_1, may or may not be a good estimator of f_c. Typical values of f_1 for three classifications of bare soil are shown in Table 4-7. For vegetated soils, the values in Table 4-7 should be multiplied by the vegetation cover factors presented in Table 4-8.

TABLE 4-7

TYPICAL f_1 VALUES FOR BARE SOILS

Soil Classification	f_1 (inches/hour)
Sands and other soils with open structures	0.50 - 1.00
Loams typical of better agricultural regions	0.10 - 0.50
Clays and other soils with dense structures	0.01 - 0.10

From American Society of Civil Engineers (1949)

TABLE 4-8

VEGETATION COVER FACTORS

Vegetation Type	Cover Quality	Cover Factor
Permanent forest and grass	Good	3.0 - 7.5
	Medium	2.0 - 3.0
	Poor	1.2 - 1.4
Close-growing crops	Good	2.5 - 3.0
	Medium	1.2 - 2.0
	Poor	1.1 - 1.3
Row crops	Good	1.3 - 1.5
	Medium	1.1 - 1.3
	Poor	1.0 - 1.1

From American Society of Civil Engineers (1949)

4.2.5.5 Measurement of Infiltration

The measurement of infiltration in the field is discussed by Bertrand (1965). Infiltration rates, capacities, coefficients, etc., can be estimated for specific existing sites from data gathered during various types of field investigations. For example, infiltrometer studies employing rainfall simulators or small area flooding techniques can be used to determine in situ infiltration rates. Unfortunately, different experimental procedures may result in substantially different estimates for the same site.

Infiltration can also be estimated indirectly from precipitation data and runoff hydrographs. However, in most cases, hydrographs that distinguish overland flow from interflow (lateral flow of perched water) are not available. Thus infiltration volumes determined by this method are usually less than what actually occurs.

4.2.5.6 Design Implications

Many of the factors that influence infiltration are not subject to control by designers and builders of hazardous-waste-site cover systems. However, notable exceptions include soil type. vegetation type, surface slope, runon control, etc. Unfortunately, trade-offs among these controllable factors complicate the design process considerably. For example, dense bare soils placed on steep slopes will initially impede infiltration, but are subject to severe erosion problems. On the other hand, a good grass cover on a loamy soil will effectively control erosion, but will retard runoff and promote infiltration. However, the grass will also serve to remove water from the cover system via transpiration. Thus, it should be clear that designing and evaluating cover systems are complex processes that require careful consideration of many competing factors.

The foregoing discussion emphasizes the importance of choosing a comprehensive design and evaluation procedure that allows one to predict cover system performance from data of the type available during the design phase of a project. Two such procedures are presented in the section on methods of water-balance analysis.

Another important practical item is the way infiltration rate varies with time. Referring to Figures 4-8 and 4-9, note that as a rainstorm continues, infiltration rate declines to a certain level and then remains there, regardless of the duration or intensity of the storm. Any excess water delivered by a long or hard rain does not infiltrate but leaves the system as runoff. It does not affect the internal structure of the cover but only the surface-water collection and drainage system. Thus the latter, but only the latter, must be designed with emergency flow rates in mind.

4.2.6 Evapotranspiration

Evapotranspiration is the principal means by which soil moisture is removed from vegetated soil. The process is quite complex, and the nomenclature used in describing it can be confusing. Therefore, brief definitions of some of the more commonly used terms are presented below. Evapotranspiration proceeds rapidly with high temperatures, direct sunlight, strong winds, and a dry atmosphere. Active evapotranspiration correlates, thus, with the spring and summer portion of the annual cycle and, on a smaller scale, with the daytime portion of the diurnal cycle. Certain regions regularly experience very windy seasons; evapotranspiration proceeds actively during such times. Along with timewise variations, there are local geographic variations also: evapotranspiration is more active (in the northern hemisphere) on south-facing than on north-facing slopes. An excellent discussion of evapotranspiration is presented by Chow (1964).

4.2.6.1 Basic Principles and Nomenclature

Evaporation is the process by which water is converted from the liquid into the gaseous state through the transfer of heat energy. The term soil evaporation is used to describe the evaporation of water that has infiltrated into the soil, and the term surface evaporation to describe the evaporation of water from pools, depressions, or plant or soil surfaces.

Transpiration is the process by which water that has been absorbed from the soil by plants is released to the atmosphere. The vast majority of the total water transpired escapes through small openings (called stomata) in the leaves. Evapotranspiration is a collective term used to denote the combination of evaporation and transpiration. For a hazardous-waste disposal-site cover system, evapotranspiration may be considered to be the sum of surface and soil evaporation and plant transpiration. Of these three components, transpiration is almost always much more important quantitatively than the other two.

Consumptive use is a term used frequently by agronomists and others interested in agricultural production. Usually, it represents the sum of all the water absorbed by plants (whether incorporated into cellular material or transpired) plus that evaporated from plant, soil, or snow surfaces, or from surface depressions. Thus, the terms evapotranspiration and consumptive use are often used interchangeably.

Pan evaporation is defined as the amount of water evaporated from a standard container, called a pan, under ambient climatological conditions. The U. S. Weather Service uses what is called class A standard pan. The class A standard pan is made of unpainted galvanized iron, is 4 ft in diameter, 10 in. deep, and is suspended 6 in. above the surface of the ground on a wooden frame. The water level in the pan is kept at 2 to 3 in. below the rim and is measured each day by means of a hook gauge. The Weather Service collects pan evaporation data routinely at numerous sites, as do other agencies. Summary data are widely available in hydrology textbooks and are presented in the

Climatic Atlas of the United States (National Oceanic and Atmospheric Administration, 1974). Historical data for specific locations are available from the National Climatic Center as well as agricultural and climatologic research facilities.

Potential evapotranspiration is defined as the evapotranspiration that may be expected so long as the supply of soil moisture to plants is essentially unrestricted. However, the rate at which evapotranspiration can actually occur is severely limited when soil moisture content drops much below field capacity, because plants have increasing difficulty in obtaining water. Thus, actual evapotranspiration, that is, the amount of water actually transpired and evaporated under the existing conditions, cannot exceed potential evapotranspiration.

As a rule, evapotranspiration at a given location exhibits a cyclical pattern having an annual period. While several factors may be important, this pattern is influenced most dramatically by the growth cycle of the vegetation. Thus, the lowest evapotranspiration rates generally occur in the winter when the growth rate is nil, and the highest rates occur during the summer at the peak of the growing season.

4.2.6.2 Estimating Evapotranspiration

Surface-water hydrologists have given much attention to estimating evaporation from free water surfaces such as streams, lakes, and reservoirs. However, while numerous theoretical and empirical equations have been published, this kind of evaporation is usually estimated directly from pan evaporation data. For example, reservoir or lake evaporation has been observed to be reasonably well approximated as about 70 percent of pan evaporation for the same site. While free water surface evaporation is only a small part of the total evapotranspiration from a vegetated area, it is interesting to note that potential evapotranspiration is also fairly well approximated as 70 percent of pan evaporation. Thus, at least during the wetter portions of the year, it may be possible to estimate evapotranspiration from a hazardous-waste disposal-site cover system using this rule of thumb. However, it must be remembered that as the soil moisture content drops appreciably below field capacity, the rate at which evapotranspiration can occur will be severely limited by the availability of water to plants.

A number of theoretical and empirical equations for estimating evapotranspiration from vegetated soil systems have appeared in the literature. Several of the more commonly used ones are presented and discussed by Chow (1964). One of the most useful expressions is the Penman equation as modified by Ritchie (1972) and presented below.

$$PET = \frac{1.28(A)(H)}{25.4(A + 0.68)} \qquad (4.16)$$

9 3 1 2 9 0 4 1 0 4 4

where

PET = the potential daily evapotranspiration (inches),
A = the slope of the saturation vapor pressure curve,
H = the net daily solar radiation (langleys).

(A langley is a unit of solar radiation equivalent to one gram calorie per square centimeter of irradiated surface.) The slope of the saturation vapor pressure curve, A , may be estimated from the following expression.

$$A = \frac{5304}{(T)^2} (e)^{(21.255 - 5304/T)} \tag{4.17}$$

where

T = the mean daily temperature (°K).

(Temperature conversion: °K = °C + 273; e.g., 293°K = 20°C.) The net daily solar radiation, H , may be estimated from the following equation.

$$H = \frac{(1 - L)(R)}{58.3} \tag{4.18}$$

where

L = the albedo for solar radiation,
R = the incident daily solar radiation (langleys).

Values of average albedo (portion of incident radiation that is reflected) for various types of land surface may be found in textbooks in climatology and hydrology (e.g., Critchfield, 1974).

Thornthwaite and Mather (1957) introduced an empirical method for estimating evapotranspiration from bare soil and vegetated areas, which has been widely used. The principal disadvantage to the method is that extensive tables found in the original reference (Thornthwaite and Mather, 1957) are required to make the estimates. This technique is part of the manual water-balance method discussed below. Example applications are given in Fenn, Hanley, and DeGeare (1975).

In summary, evapotranspiration accounts for the major portion of the soil moisture lost from a typical well-vegetated cover system. Thus, care should be used in arriving at the numerical values used in estimating percolation. Water-balance methods that take into account the fact that evapotranspiration rate is a function of soil moisture content are much to be preferred. Both the methods discussed below include this feature. The computerized method calculates potential evapotranspiration by equation (4.16), but limits actual evapotranspiration, depending upon the availability of soil moisture to the vegetation. The manual method makes use of the Thornthwaite method (Thornthwaite and Mather, 1957), which also takes soil moisture content into account.

4.2.7 Methods of Water-Balance Analysis

As previously discussed, virtually all methods of estimating leachate production or percolation require some form of water-balance procedure. The principal factors that affect the difficulty involved are the quantity and quality of the data available and the accuracy desired. Two published procedures are considered below. The first is a manual technique that is suitable for constructing a monthly water balance. While greater accuracy could be obtained by using a daily time period, the monthly procedure is very useful in that it requires a minimum of data and effort, and has been shown to produce reasonable results. The second procedure considered is an easy-to-use computer model that operates on a daily time period. Lutton, Regan, and Jones (1979) discuss other water-balance procedures applicable to cover systems.

4.2.7.1 A Manual Water-Balance Method

Fenn, Hanley, and DeGeare (1975) have published a simplified manual procedure that can be conveniently used to construct a monthly water balance for a hazardous-waste disposal-site cover system. While the method can also be used with a daily time period, such a use would appear impractical given the computational effort involved.

(1) Estimating percolation. Percolation is calculated by a simple mass-balance procedure after other components of the water budget have been determined. The fundamental mathematical relationship may be expressed as shown below.

$$PERC = P - RO - CST - AET \tag{4.19}$$

where

PERC = percolation,
P = precipitation,
RO = surface runoff,
CST = change in soil-moisture storage,
AET = actual evaporation.

All terms in equation (4.19) must be expressed in the same units. The general procedure to be used with equation (4.19) is summarized below. For more detailed discussion, complete with numerical examples, see Fenn, Hanley, and DeGeare (1975).

Precipitation data corresponding to the selected time period must be used. For a monthly balance, the logical choice is historical mean monthly precipitation if the goal is to estimate average percolation production. However, if it is desired to estimate peak rates of percolation, hypothetical data for a very wet year may be used. Thus, the choice of precipitation data depends upon the intended use of the results.

Surface runoff is estimated directly from precipitation by means of runoff

coefficients. Typical coefficients are presented above in the section on runoff. Infiltration, I , is estimated indirectly as the difference between the precipitation, P , and the runoff, RO (i.e., I = P-RO).

The potential evapotranspiration, PET , is estimated by the Thornthwaite method (Thornthwaite and Mather, 1955, 1957). This technique requires the use of tables presented in the references indicated. The potential evapotranspiration may be thought of as the maximum evapotranspiration that can occur, assuming an unlimited supply of soil moisture.

The difference between the estimated infiltration and the potential evapotranspiration (i.e., [I-PET]) is used to determine whether the soil-moisture storage should increase or decrease during a given month. A negative value of [I-PET] indicates that infiltration is not sufficient to meet the evapotranspirative demand, and hence, soil-moisture storage may be expected to decrease, assuming that plant-available water is present. A positive value of [I-PET] indicates that more water infiltrates than can be lost to evapotranspiration. Thus, soil-moisture storage must increase, unless the soil moisture content is already at field capacity.

In most locations there is an annual wet/dry cycle. Thus, the soil-moisture storage for the last month in the yearly cycle having a positive value of [I-PET] may be assumed to correspond to the field capacity. That is, the soil-moisture storage at the end of that month may be estimated as the product of the depth of the soil and the dimensionless field capacity. Normally, only the soil depth corresponding to the root penetration zone is considered.

The assumption that soil moisture is at field capacity at the end of the last month having a positive value of [I-PET] (i.e., the end of the wet period) is a reasonable one, and is very convenient since it is necessary to begin the actual water-balance calculations with some known value of soil-moisture storage. Thus, this provides a logical starting point.

Once a starting point has been determined, the soil-moisture storage at the end of the wet season, it is possible to estimate the amount of percolation to be expected for each month using equation (4.19). However, for months when [I-PET] is negative, actual evapotranspiration is limited by the amount of soil moisture available for plant use. Thus, during these months, actual evapotranspiration, AET , is less than PET . Tables provided in Thornthwaite and Mather (1955, 1957) may be used to estimate the change in soil-moisture storage that may be expected under these circumstances. AET may then be estimated as the difference between infiltration and the change in soil-moisture storage (i.e., [I-CST]).

Negative values of percolation, PERC , will be predicted by equation (4.19) so long as the soil moisture content is less than the field capacity. These negative values have no direct physical significance and may, thus, be replaced by zeros.

(2) Estimating leachate production. Percolation, estimated as above, represents water that percolates through the cover system. Since lateral outflow is not considered, it follows that this water will then enter underlying

soil or water layers and ultimately become leachate. The time lag between the closure of a waste site and the beginning of leachate production may be estimated if the initial moisture contents of all underlying soil and waste layers are known. That is, these layers may be expected to fill gradually with moisture as percolation enters from above. When the moisture content of a given layer reaches field capacity, percolation will begin to pass into the next lower layer. Ultimately leachate is assumed to be generated at a rate equal to the rate at which moisture percolates through the cover system.

(3) Case studies. Three instructive case studies were worked out and presented by Fenn, Hanley, and DeGeare (1975), for Cincinnati, OH, Orlando, FL, and Los Angeles, CA, cities representing three different climates. Interestingly, there is less percolation at Orlando than at Cincinnati, even though Orlando has higher annual precipitation. The reason is that high precipitation and high evapotranspiration are nearly in phase, with respect to the yearly cycle, in Orlando (rain concentrated in the summer months), while they are not similarly in phase in Cincinnati (precipitation more nearly constant throughout the year). At Los Angeles, with a dry climate, no percolation is to be expected from the natural rainfall. However interestingly also, if the final land use of a site in Los Angeles were to be a park, where grass were watered by irrigation, a considerable amount of percolation might be produced thereby.

4.2.7.2 The HELP Model

The Hydrologic Evaluation of Landfill Performance (HELP) program is an easy-to-use, computerized water-budget model that was developed to assist landfill designers and regulators by providing a tool to allow rapid, economical screening of alternative designs. The program may be used to estimate the magnitudes of various components of the water budget, including the volume of leachate produced and the thickness of water-saturated soil (head) above barrier layers. The results may be used to compare the leachate-production potential of alternative designs, select and size appropriate drainage and collection systems, and size leachate-treatment facilities. The program was designed primarily for interactive use, but may be run in a batch mode.

HELP uses climatologic, soil, and design data to produce daily estimates of water movement across, into, through, and out of landfills. To accomplish this, daily precipitation is partitioned into surface storage, runoff, infiltration, surface evaporation, evapotranspiration, percolation, stored soil moisture, and subsurface lateral drainage. Surface runon and subsurface lateral inflow are not considered. Complete documentation and a user's guide are available in Schroeder, Gibson, and Smolen (1984), and Schroeder et al. (1984).

(1) Hydrologic processes. Runoff is computed using the Soil Conservation Service Runoff Curve Number method described above. Factors such as surface slope and roughness are not considered directly in estimating runoff, and hence infiltration. However, they may be taken into account in the selection of a curve number. This approach to runoff estimation is made possible by

considering only daily precipitation totals, and not the intensity, duration, and distribution of individual rainfall events (storms).

Percolation and vertical water routing are modeled using Darcy's Law for saturated flow with modifications for unsaturated conditions. Lateral drainage is computed analytically from a linearized Boussinesq equation corrected to agree with numerical solutions of the nonlinearized form for the range of design specifications used in hazardous-waste landfills. Evapotranspiration is estimated by a modified Penman method adjusted for limiting soil moisture conditions. Detailed solution methods for all hydrologic processes are presented in the program documentation (Schroeder, Gibson, and Smolen, 1984).

(2) Data requirements. The HELP program requires climatologic, soil, and design data. However, sufficient default climatologic and soil data are internally available to satisfy the needs of many users. The basic data requirements and input options are briefly discussed below.

(a) Climatologic data. Climatologic data, including daily precipitation in inches, mean monthly temperatures in °F, mean monthly insolation (solar radiation) in langleys, leaf area indices, and winter cover factors, may be entered manually or selected from built-in "default" data files. Leaf area indices and winter cover factors are variables used to describe the condition of vegetative cover crops with respect to their effects on evapotranspiration. They are discussed further below.

Default climatologic data consisting of five years (1974-78) of observed daily precipitation and one set of values for mean monthly temperature, mean monthly insolation, leaf area index, and winter cover factor for each of 102 U. S. cities are built into the program. These data may be accessed and used simply by giving appropriate responses to straightforward program queries.

The default climatologic data base includes values for two variables that relate to the effects of vegetation on evapotranspiration; leaf area index (LAI) and winter cover factor. LAI is defined as the (dimensionless) ratio of the leaf area of actively transpiring vegetation to the nominal surface area of land on which the vegetation is growing. The HELP program assumes that LAI may vary from a minimum value of 0 to a maximum value of 3. The former is representative of no actively growing vegetation (i.e., bare ground or dormant vegetation), and the latter represents the most dense stand of actively growing vegetation considered. Default LAI data sets consist of 13 Julian dates (spaced throughout the entire year) and corresponding maximum LAI values for a good row crop and an excellent stand of grass. A different set of LAI data is provided for each of the 102 cities. The program adjusts these maximum values downward if necessary, depending upon the vegetative cover specified, and interpolates for daily values in order to model evapotranspiration during the growing season. For the remainder of the year, transpiration is assumed not to occur. However, even dormant vegetation can serve to insulate the soil, and thus affect evaporation. Winter cover factors, which vary from 0 for row crops to 1.8 for an excellent stand of grass, are used to account for this effect.

When the manual climatologic data input option is utilized, the user must

provide daily precipitation data for each year of interest. The maximum allowable period of record is 20 years and the minimum is 2 years. A separate set of temperature, insolation, LAI, and winter cover factor may be entered for each year, or a single set of data may be used for all years.

(b) Vegetative cover data. The user must specify an evaporative (root) zone depth and, if a default option is used, one of seven types of vegetative cover. Acceptable default types of vegetation are bare ground (i.e., no vegetation), excellent, good, fair, and poor stands of grass, and good and fair stands of row crops. Depending upon the default vegetation type selected, the hydraulic conductivity of the soil within the evaporative zone is corrected for the effects of roots by multiplication by a factor varying from 1 for bare ground to 5 for an excellent stand of grass. The LAI values discussed above are also modified depending upon the type of vegetation specified.

(c) Design and soil data. The user must specify data describing the various materials contained in the landfill (e.g., topsoil, clay, sand, waste) and the physical layout (design) of the landfill (e.g., size, thickness of various layers, slopes, etc.). Either the default or manual input options may be utilized for soil data; however, design data must be entered manually.

The HELP program may be used to model landfills composed of up to nine distinct layers. However, there are some limitations on the order in which the layers may be arranged, which must be observed if meaningful results are to be obtained. Also, each layer must be identified as either a vertical-percolation, lateral-drainage, waste, or barrier-soil layer. This identification is very important because the program models water flow through the various types of layers in different ways. However, in all cases, the program assumes that each layer is homogeneous with respect to hydraulic conductivity, transmissivity, wilting point, porosity, and field capacity. A typical closed-landfill profile is shown on Figure 4-11. The circled numbers indicate the layer identification system used by the program.

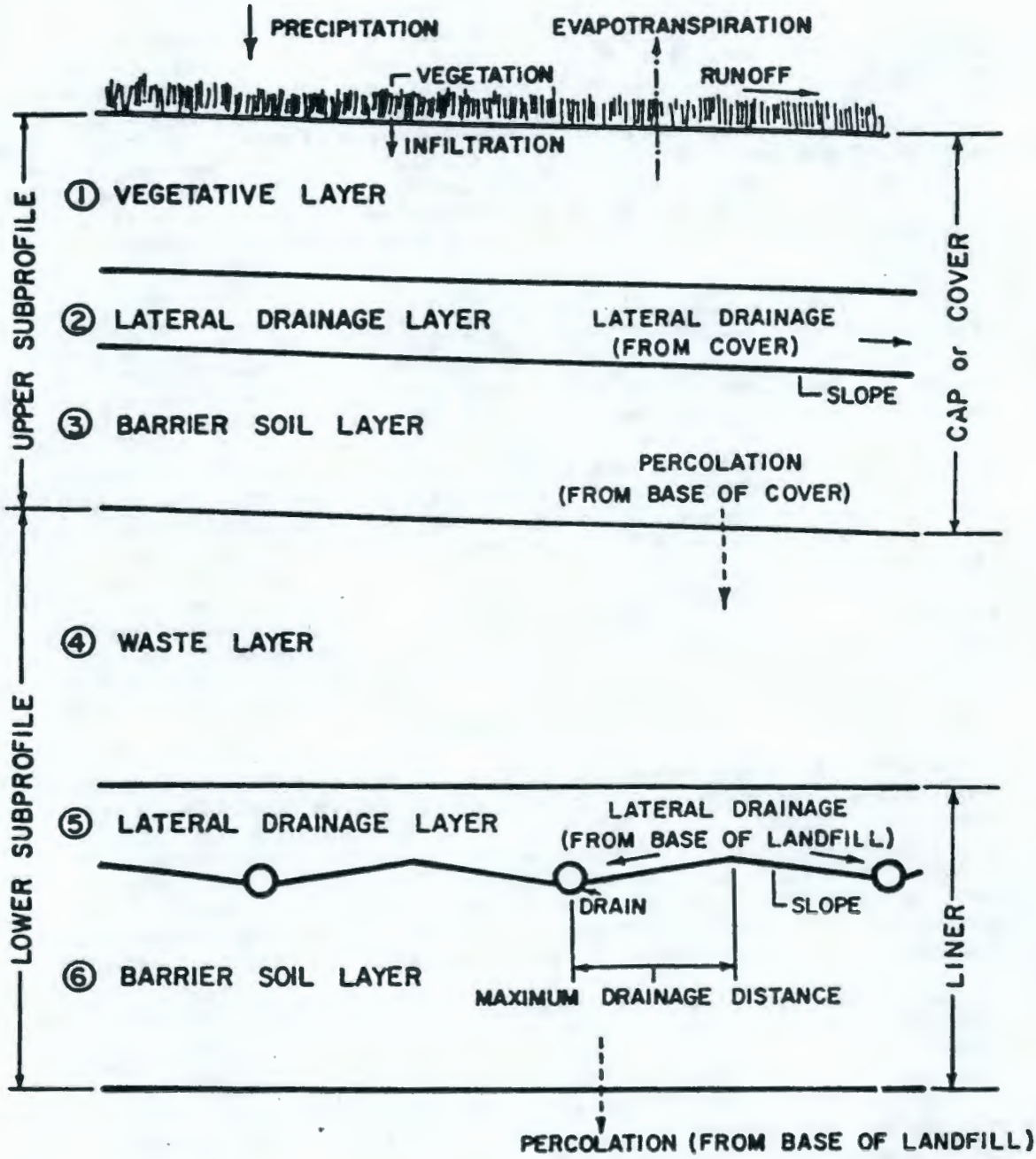
Vertical-percolation layers (e.g., layer 1 on Figure 4-11) are assumed to have hydraulic conductivity sufficiently great that vertical flow in the downward direction (i.e., percolation) is not significantly restricted. Lateral drainage is not permitted, but water can move upward and be lost via evapotranspiration, depending upon the specified depth of the evaporative zone. Percolation is modeled as being independent of the depth of water-saturated soil (i.e., the head) above the layer. Layers designed to support vegetation should generally be designated as vertical-percolation layers.

Lateral-drainage layers are assumed to have hydraulic conductivity high enough that little resistance to flow is offered. Therefore, the hydraulic conductivity of a drainage layer should be equal to or greater than that of the overlying layer. Vertical flow is modeled in the same manner as for a vertical-percolation layer, however lateral outflow is allowed. This lateral drainage is considered to be a function of the slope of the bottom of the layer, the maximum horizontal distance that water must transverse to drain from the layer, and the depth of water-saturated soil above the top of the underlying barrier-soil layer. The slope at the bottom of the layer may vary

9 3 1 2 9 0 4 1 0 5 0

FIGURE 4-11

TYPICAL LANDFILL PROFILE (SEE TEXT DISCUSSION OF HELP MODEL)



from 0 to 10 percent, and the maximum drainage distance may range between 25 and 200 ft. Layers 2 and 5 on Figure 4-11 are lateral-drainage layers.

Barrier-soil layers serve the purpose of restricting vertical flow. Thus, such layers should have hydraulic conductivity substantially lower than for vertical-percolation, lateral-drainage, or waste layers. The program limits the direction of flow in barrier-soil layers to downward. Thus, any water moving into a barrier layer will eventually percolate through. Percolation is modeled as a function of the depth of water-saturated soil (head) above the base of the layer. The program recognizes two types of barrier layers; those composed of soil alone, and those composed of soil overlain by an impermeable synthetic membrane. In the latter case, the user must specify some membrane leakage fraction. The net effect of specifying the presence of a membrane is to reduce the effective hydraulic conductivity of the layer. The program does not model aging of the membrane. Layers 3 and 6 shown on Figure 4-11 are barrier layers.

Water movement through a waste layer is modeled in the same manner as for a vertical-percolation layer. However, identifying a layer as a waste layer indicates to the program which layers should be considered part of the landfill cap or cover, and which layers should be considered as part of the liner/drainage system. Layer 4 shown on Figure 4-11 is a waste layer.

If the topmost layer of a landfill profile is identified as a waste layer, the program assumes that the landfill is open. In this case, the user must specify a runoff curve number and the fraction of the potential surface runoff that is actually collected and removed from the landfill surface.

Important nomenclature used by the program is indicated on Figure 4-11. For computational purposes, the soil profile is partitioned into subprofiles, which are defined in relation to the location of the barrier-soil layers. For example, the upper subprofile shown on Figure 4-11 extends from the ground surface to the bottom of the upper barrier-soil layer (layer 3), while the lower subprofile extends from the top of the waste layer to the base of the lower barrier-soil layer. If an intermediate barrier-soil layer had been specified, a third (intermediate) subprofile would have been defined. Since the model can handle no more than three barrier-soil layers, there can be no more than three subprofiles. The program models the flow of water through one subprofile at a time with the percolation from one subprofile serving as the inflow to the underlying subprofile, and so on through the complete profile.

(1) Soil data. The type of soil present in each layer must be specified by the user. He can use either the default or manual data-input option. Characteristics for 18 default soil types are presented in Table 4-1. The first three columns represent, respectively, soil designations used by the HELP program, textural soil descriptions as used by the U. S. Department of Agriculture, and soil group symbols according to the Unified Soil Classification System (USCS). The numerical entries represent typical data values corresponding to the various soil types and are used by the HELP program, as needed, for computational purposes. Default soil data may be accessed and used simply by entering the appropriate soil-texture number in response to a command from the program.

9 3 1 2 9 0 4 1 0 5 2

The user may also enter soil characteristics manually. In this instance, the program will require that numerical values be entered for porosity, field capacity, wilting point, hydraulic conductivity (i.e., saturated hydraulic conductivity) in inches per hour, and evaporation coefficient in millimeters per square root of day. (Note: porosity, field capacity, and wilting point are all dimensionless.)

(2) Soil compaction. Barrier-soil layers and waste layers may be compacted to restrict the vertical flow of water. When using the default soil-data option, the user has the option of specifying that any layer is to be considered compacted. When a layer is so identified, the hydraulic conductivity is reduced by a factor of 20, and the drainable water (i.e., porosity minus field capacity) and plant-available water (i.e., field capacity minus wilting point) are each reduced by 25 percent. When using the manual soil-data option, the user simply enters soil data representative of compacted soil. Layers that support vegetation should not be compacted.

(3) Design data. The user must enter the total surface area of the landfill to be modeled in square feet, and the thickness of each layer in inches. For drainage layers, the slope of the bottom of the layer and the maximum horizontal drainage distance must also be supplied. The former may vary from 0 to 10 percent and the latter from 25 to 200 ft. When drain tiles are to be used, the appropriate distance is one half the maximum spacing. When drains are not used, the appropriate distance is the maximum horizontal distance that water must travel to reach a free discharge. Depending upon the soil profile chosen and the input option selected, other data such as runoff curve number, membrane leakage fraction, and potential runoff fraction may be requested by the program.

(4) Program output. Basic program output, always reported, consists of the following: all default and manual input information except daily precipitation data, and summary results. Input data has been described above. Summary output data are described below. Occasional reference to Figure 4-11 may be helpful in understanding some of the terminology used in describing program output.

(a) Summary output. Following the input-data summary, the program produces a table of annual totals for each year of operation simulated. Specific entries appearing in the tables include total annual precipitation, runoff, evapotranspiration (total of surface and soil evaporation and plant transpiration), percolation through the base of each subprofile, and lateral drainage from each subprofile. Each of these output variables is reported in terms of inches, cubic feet, and as a percent of total annual precipitation. The soil moisture content and precipitation stored in the form of snow are reported for the beginning and the end of the year in terms of inches and cubic feet.

After the annual-total tables, the program reports average monthly totals for each of the output variables noted above except soil moisture content and precipitation stored as snow. All values are reported in terms of inches. The entries shown indicate averages of the monthly totals for all years

simulated, for example, the average total runoff in July for the period simulated (say five years).

The next table presents average annual totals for the total period simulated. Average annual values for precipitation, runoff, evapotranspiration, percolation through the base of each subprofile, and lateral drainag from each subprofile are reported in terms of inches, cubic feet, and as a percent of total average annual precipitation.

In the final table, peak day values for precipitation, runoff, percolation through the base of each subprofile, lateral drainage from each subprofile, and precipitation stored in the form of snow are reported in terms of inches and cubic feet. The maximum head on the base of each subprofile and the maximum and minimum soil moisture content for the vegetative layer are also reported in terms of inches.

The data reported in these summary tables are sufficient for rapidly screening alternative designs and roughly sizing drainage and leachate collection and treatment systems. However, more detailed information may be obtained by requesting monthly or daily output.

(b) Detailed output. When the user requests monthly output, tables are produced which report monthly totals (in terms of inches) for precipitation, runoff, evapotranspiration, percolation through the base of each subprofile, and lateral drainage from each profile for each year included in the simulation.

When daily output is requested, daily values are reported for the Julian date, precipitation, runoff, evaporation, head on the base of the cover, percolation through the base of the cover, lateral drainage from the cover, head on the base of the landfill, percolation through the base of the landfill, lateral drainage from the base of the landfill, and the soil moisture content of the evaporative zone. Where applicable the units are inches, except for soil moisture, which is reported in dimensionless form (i.e., as a fraction of the maximum possible value). An additional variable is reported to indicate if the temperature is above or below freezing (32°F).

4.2.7.3 Some General Comments on Water-Balance Methods

In virtually all water-balance methods, individual processes that affect the water balance are considered separately (to the extent possible), and then their individual contributions are summed to produce a mass balance for the system considered. Usually, soil moisture content is calculated by these means, and then leachate production (percolation) is estimated from the change in soil moisture storage. Thus, inaccuracy in any estimates corresponding to the individual processes considered will result in inaccuracy in the final estimate of leachate production or percolation. For this reason, care must always be exercised to ensure that each component of the water budget is given ample consideration. In the majority of cases, leachate production (or percolation) will be only a small fraction of the total water accounted for in the

9 3 1 2 9 0 4 1 0 5 4

balance. Thus, a relatively small error in estimating the contribution of one component (e.g., a 10 percent error in estimating evapotranspiration) can result in a relatively large (e.g., 100 percent or more) error in the estimate of leachate production or percolation.

4.3 Gas Control

It may be necessary to design for control of gases when covering an uncontrolled hazardous waste site. Gases are evolved wherever decayable (biodegradable) organic matter is buried; thus gas control is a problem at nearly all municipal landfills. Where municipal and hazardous wastes were dumped at the same site, a gas problem is likely. Where no decayable matter was buried, gas will probably not be a problem.

4.3.1 Gas Generation

Organic refuse may generally be classified into three groups (Rovers, Tremblay, and Mooij, 1977). The rapidly decomposing component comprises food stuffs and garden waste; the intermediate-decomposing component comprises paper and wood waste; and the refractory component comprises plastic and rubber. The first group contains about 30 pct of the biodegradable waste, which decays in a landfill over a period of from one to five years. The second group contains about 70 percent of the biodegradable waste and has a degradation half-life of 5 to 25 years. Thus the rate of waste gas production decreases steadily, but some production may persist for many years.

Within a few months of closure of a landfill, anaerobic decay conditions stabilize, and thereafter only two gases are produced in appreciable quantity: methane (CH_4, about 55 pct by volume) and carbon dioxide (CO_2, about 45 pct by volume). Trace quantities of other gases may also be produced.

The most serious problem from waste gases is explosion hazard. Methane (and some of the trace gases) is combustible, and methane-air mixtures are explosive over a certain range of composition (about 5 to 15 pct methane by volume). An explosion hazard develops when methane migrates from a landfill and becomes mixed with air in a confined space. Several tragic methane explosions caused by landfill gases have occurred in recent years (Shafer et al. 1984).

Other actual or potential threats from waste gases include vegetation distress, odor problems, property-value deterioration, physical disruption of the cover, and toxic vapors. Vegetation kills are a demonstrated fact at landfill covers. The exact damage mechanism may be complex, involving oxygen starvation (asphyxiation), temperature increase, plant toxicity, etc. Carbon dioxide as well as methane may be responsible for vegetation damage. The offensive odors of landfill gases are often attributable to trace gas components, such as hydrogen sulfide and mercaptans. Property values near a landfill may deteriorate largely from the threat of waste gases (Rovers, Tremblay,

and Mooij, 1977). The threat of physical disruption of the cover should not be discounted. Given a highly impermeable cover and sufficient production of gas, the gas must escape somewhere, and it will do so in an uncontrolled fashion if no controlled exit is provided.

4.3.2 Vapors

Where toxic substances are buried in the absence of decaying organic matter, the threat of their vapors* reaching the surface in dangerous quantities appears to be very small. In an occurrence of hexachlorobenzene (HCB) dispersal traceable to landfill dumping (Farmer et al., 1976), elevated levels of HCB were found in plants, cattle, and humans living near a Louisiana landfill. However, the problem may have developed during a period of careless haulage and open dumping. Laboratory studies indicated that a soil cover would probably reduce the rate of HCB volatilization, relative to that from exposed material, by a factor of several thousand. The chief problem would be maintenance of the integrity of the cover. The rate of migration of a vapor should be very much lower than that of a gas such as methane or carbon dioxide, because of the much higher equilibrium pressure of the latter at any given temperature. Therefore, it seems logical to expect that migration of a vapor from beneath a soil cover would rarely lead to a hazardous situation. The detection and measurement of organic substances over waste sites has been a matter of recent research in California (Karimi, 1983). Vapor diffusion through cover soils at landfills is discussed in Farmer et al. (1980).

4.3.3 Gas Treatment and Control

Landfill gases have received considerable attention in the literature, not only as a problem but also as a potential energy source (Rovers, Tremblay, and Mooij, 1977; Intergovernmental Methane Task Force, 1979; Shafer et al., 1984; Lutton, Regan, and Jones, 1979; and other sources cited in the above). A considerable body of experience with controlling landfill gas has accumulated. The field is young, however, and any design must be highly site-specific. The cover designer may find it advisable to consult a contractor or consultant with experience in the field.

An excellent discussion of gas migration control at waste disposal sites may be found in Chapter 6 of JRB Associates (1982) or Rogoshewski, Bryson, and Wagner (1983).

A factor that needs to be considered is the possible fouling of gas drainage systems by the growth of a biomass of anaerobic slimes (E. Glysson, lecture at University of Wisconsin Extension, October 1982). This problem has occurred at gas drainage wells at municipal landfills. Such slimes will grow as coatings on mineral particles. The larger the pore sizes in the gas drainage

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* Vapor is defined as a gas below its critical point (Daniels and Alberty, 1961, p. 125).

9 3 1 2 9 0 4 1 0 5 6

layer, the longer it takes a buildup to block the pores completely. Thus, the coarser the material in the gas-drain layer, the better.

Guidance may be found in the above-cited references. Gas-control systems make use of natural barriers when possible and of constructed barriers such as trenches, membranes, wells, and vents. The cover designer should remember, however, that at a hazardous waste site, not all measures may be acceptable. Engineering judgment is required, depending on the specifics of the site.

The following guidance is taken from Rovers, Tremblay, and Mooij (1977). Their report was the outgrowth of an international seminar held in Montreal to consider the problem of landfill gas monitoring and control.

Natural barriers to gas migration include moist, fine-grained soils and saturated coarse-grained soils. Lateral methane migration can be naturally controlled at a landfill boundary by fine-grained soils, such as glacial till or natural clay deposits, and by the water table.

Constructed control systems include trenches to the water table, permeable trenches with or without impermeable membranes, induced exhaust or gas-extraction systems, and vertical venting.

At small sites situated within coarse-grained soils having a shallow ground-water table, lateral methane migration can be controlled at a site boundary by open trenching around the fill down to the water-table depth.

A permeable gravel-filled trench (see Figure 4-12, 'A') may be an effective lateral migration control system at an existing refuse disposal site situated in less permeable soil having a deep water table. The trench should be constructed to a depth at least equal to the depth of the landfill. In areas where freezing and sealing of the trench cover can occur, the permeable trench should be outfitted with vent pipes.

In permeable soils, a permeable trench should be provided with an impermeable barrier (see Figure 4-12, 'B'), such as a plastic membrane or non-swelling clays, to a depth at least equal to the base of the landfill. Pipe venting (see Figure 4-12, 'C') should be provided between the landfill and the impermeable barrier in areas where freezing and sealing of the trench or land surface may occur.

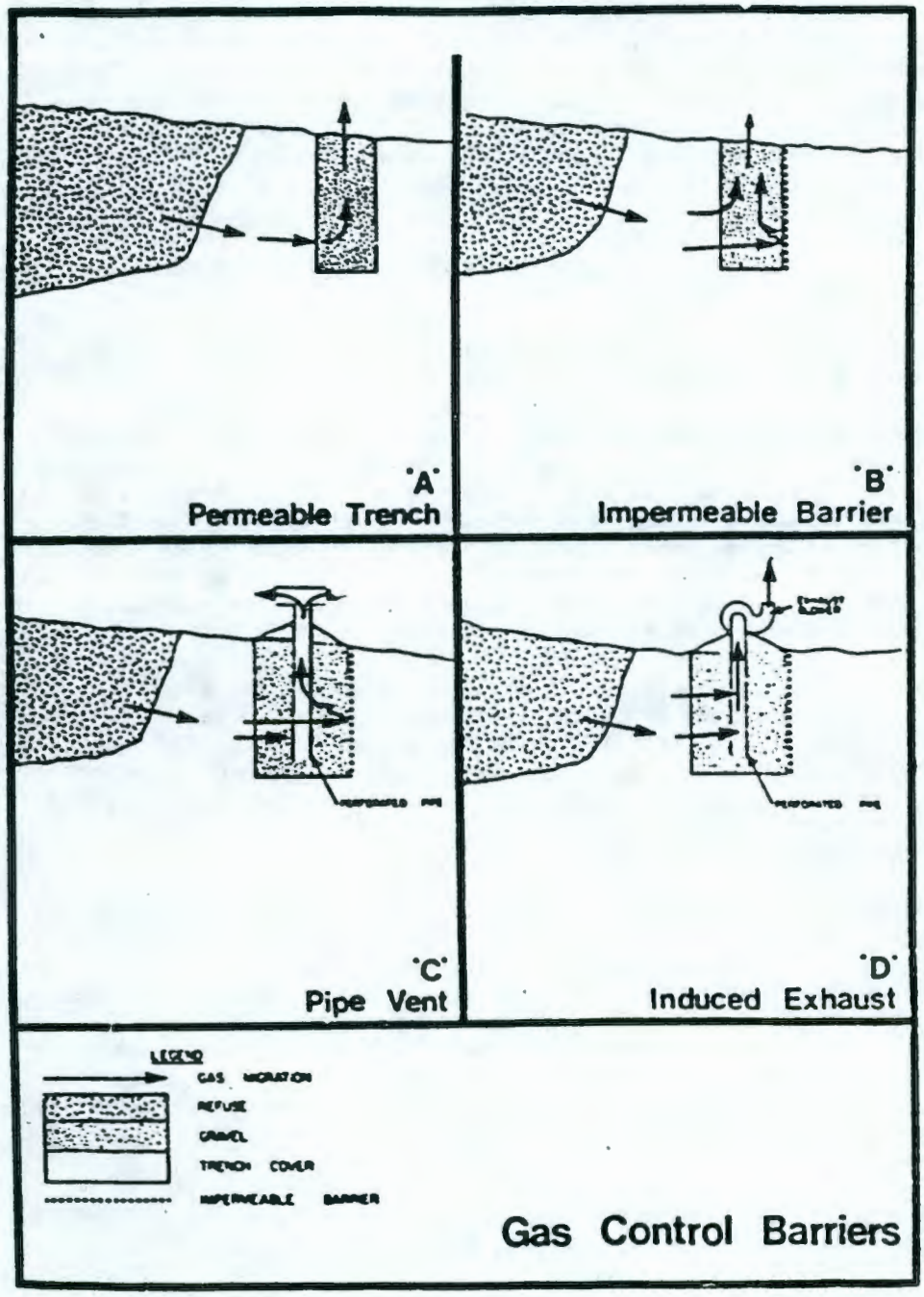
An induced exhaust system (see Figure 4-12, 'D'), consisting of a permeable trench equipped with gas vents or separately installed gas wells connected by a header to an exhaust fan, is a most effective gas-control method. An induced pressure gradient of less than 1 in. of water in the header has been found to be effective in controlling lateral gas migration.

An induced gas extraction system consisting of gas wells constructed within a landfill was reported not to have been proven effective (Rovers, Tremblay, and Mooij, 1977).

Vertical vents, or gas wells, installed around the landfill at 30 to 60 ft centers and down to the base of the landfill or to the water table are

FIGURE 4-12

GAS CONTROL BARRIERS (ROVERS, TREMBLAY, AND MOOIJ, 1977)



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effective if connected to a header and exhaust fan. A usual design would be to induce a negative head of up to 10 in. of water. Gas well and header design are discussed below.

Gas extraction and recovery will probably be more commonly attempted at municipal rather than hazardous waste landfills. For recovery and utilization, gas-extraction wells are necessary. Figure 4-13 details the design of a gas-extraction well. On-site testing has shown that to get the maximum volume of gas with the maximum BTU value, the gas-extraction well should be centrally located in the refuse with a minimum screen of 10 ft. At a large landfill, multiple wells would be required. Figure 4-13 shows that in a 60-ft landfill the borehole of up to 4 ft in diameter would be drilled to a depth of 40 ft with a 20-ft well screen.

Each of the wells would be connected to a common gas-collection header equipped with an exhaust blower.

The well is equipped with a telescopic coupling to allow the well to shorten should the refuse settle.

Considerable discussion was generated at the Montreal seminar (Rovers, Tremblay, and Mooij, 1977, p. A-12) regarding the well diameter and need for the gravel pack. One opinion was that almost any well size, without a gravel pack, would suffice, while another opinion was that larger well diameters, preferably packed in gravel, were needed to prevent screen blockage either due to bacterial slime formation or chemical precipitation on the screen. It was generally agreed that a 4 to 6-in.-diam PVC well would perform adequately. It was thought that a gravel pack may not be required.

Gas from a multiple-gas-well system would be extracted via a gas-collection header installed either above or below the ground surface. Most of the gas-collection-well headers are installed below the ground surface. In some cases they are installed in trenches dug in the surface of the ground, in other cases soil is piled up around these headers. The reason for covering these headers is to protect them from external contact damage and to protect them against extreme changes in temperature.

Gas withdrawn from a landfill is saturated with moisture which condenses in the collection header. In climates where freezing can occur, this moisture must be removed from the header to prevent freezing. Figure 4-14 details two methods of moisture drainage. In the first method, the moisture is drained to a designed drainage connection. This method is most useful for installation in header pipe travelling long distances between wells or to the exhaust system from the last well. The recommended installation is every 100 ft. In the second method, collection header is sloped to drain the condensed moisture to the gas wells although it was suggested that this may interfere with the program of gas extraction.

For a more detailed discussion of gas control, the reader is referred to JRB Associates, Inc. (1982) or Rogoshewski, Bryson, and Wagner (1983).

FIGURE 4-13

GAS EXTRACTION WELL DESIGN (ROVERS, TREMBLAY, AND MOOIJ, 1977)

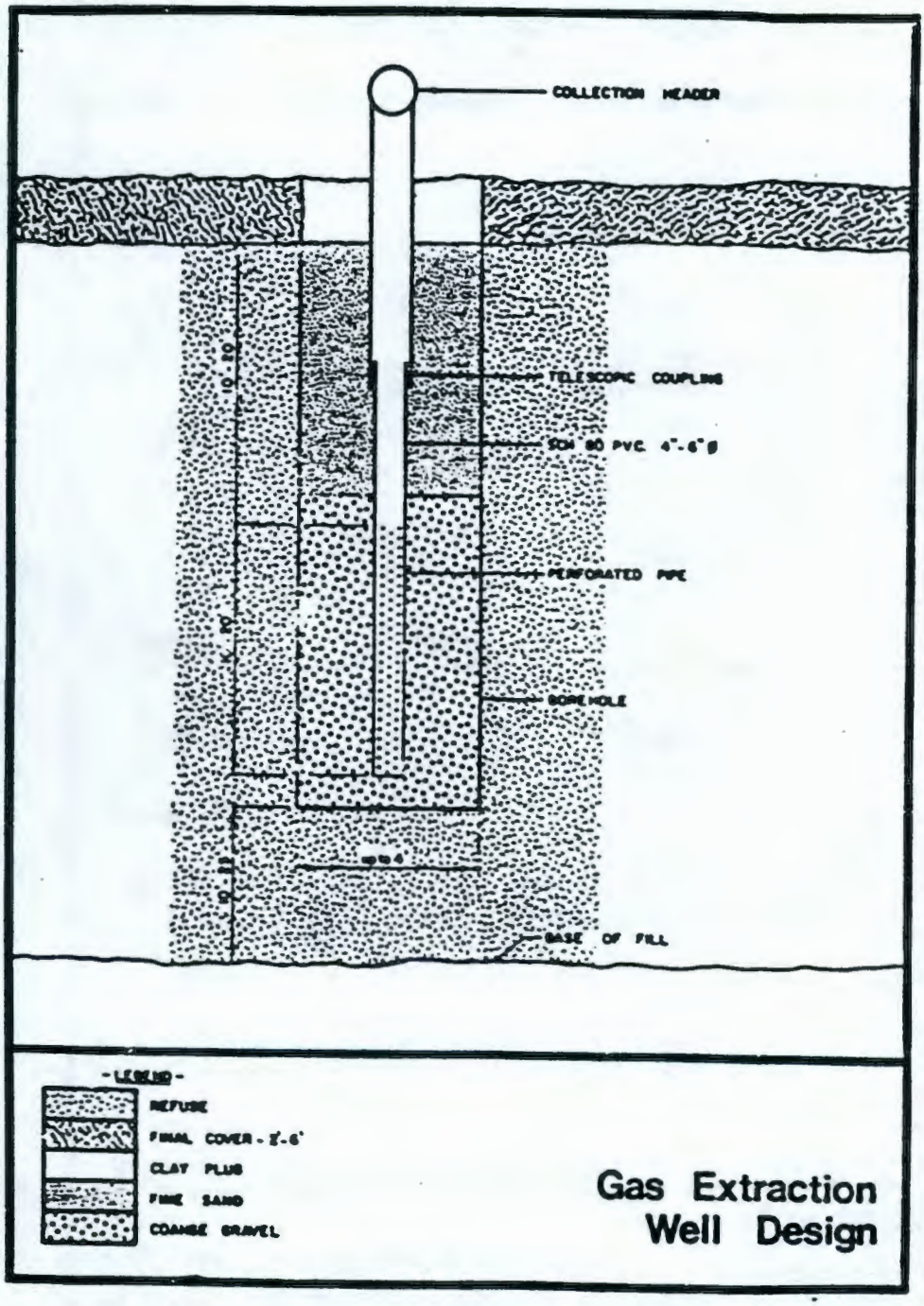

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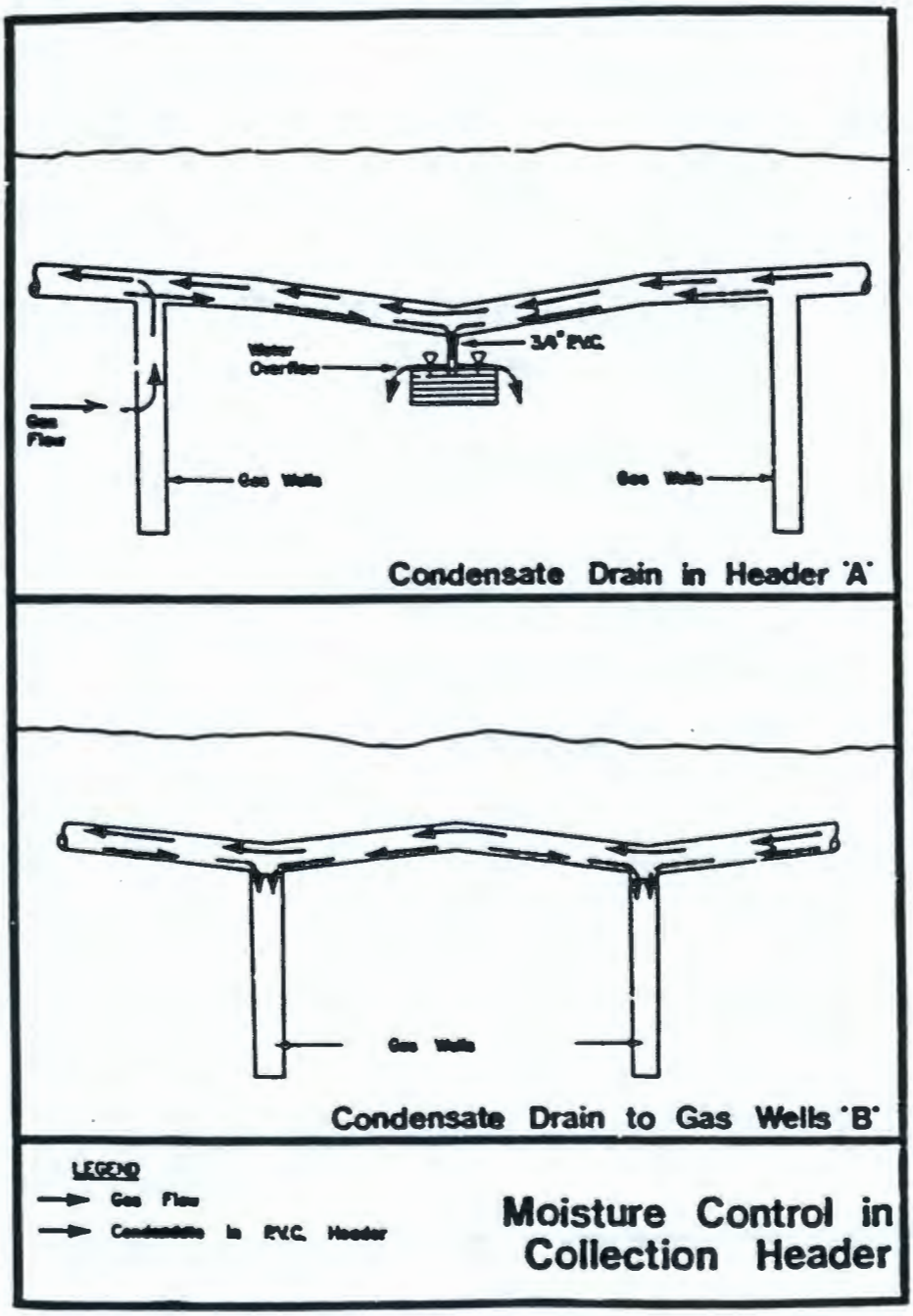
FIGURE 4-14

MOISTURE CONTROL IN COLLECTION HEADER (ROVERS, TREMBLAY AND MOOIJ, 1977)



4.4 Filter Layer(s)

4.4.1 General

A filter is a layer of material placed between two materials of contrasting gradation in order to perform one or both of the following functions:

- Prevent the migration of fine soil particles into a coarser-grained material (e.g., a riprap blanket or gravel drain).
- Allow water freely to enter a drainage medium (pipe or drainage blanket) without clogging it with fine particles of soil.

Therefore, to insure a filter's successful operation, its design must be addressed from both a stability and a permeability standpoint.

Filter layer(s) may or may not be needed in a given cover design. Places where such a layer might be required include:

- Beneath the vegetative layer and above a drainage layer.
- Beneath a clay barrier layer and above a coarse-grained gas-control layer.
- Beneath a riprap channel lining and above the fine-grained soil below the channel.

In each case the design engineer must decide on the need for a filter layer, taking into consideration the following factors:

- Contrast in gradation between adjacent materials.
- Likelihood of migration of fines.
- Consequences of such migration.

If a filter is needed, its design should follow the principles given below.

Generally two types of materials are used as filters. One type is carefully graded cohesionless soil (sands and gravels). This graded filter is attractive by virtue of its durability, long history of use as a filter medium, and relatively good availability. However, the gradation of this type of filter requires careful design, and the success depends heavily upon the precision and quality of the processing and installation procedures.

The other type of filter material is a geotechnical fabric or geotextile. Its advantages are:

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- Manufactured in a controlled environment (factory).
- Requires less design work than a granular filter.
- Relatively simple to install.
- Can be installed rapidly.
- Can be obtained in a variety of pore sizes.

However, information on geotextiles' performance in the waste-disposal field is still limited. Geotextiles do not have the history of use necessary to predict confidently what their characteristics will be after extended exposure to the conditions which could be present at a hazardous-waste site. Also, a geotextile, being a relatively thin material, is susceptible to damage during installation and the construction of subsequent cover elements over it.

4.4.2 Granular Filters

Criteria for the design of filters of either type of material are essentially empirical in nature. Testing programs have substantiated and refined these empirical criteria to a point where they may be used with confidence. Among the sources where filter criteria and discussions thereof may be found are Cedergren (1977), Department of the Army (1978), Anderson, Paintal, and Davenport (1970), and Department of the Navy (1971, 1982).

Design criteria for granular filters are given in terms of characteristic particle sizes, e.g. d_{15}, d_{85}, etc. The d_{15} size is the particle diameter such that 15 weight percent of the soil is made up of grains finer than d_{15}, etc. Characteristic particle sizes are discussed in section 3.2.5.1.

As mentioned, filter criteria apply to two areas, stability and permeability. In the stability area, the designer wishes to avoid movement of soil particles from the protected soil through the filter. The following design criteria have been established for granular filters to meet that requirement:

a. $$\frac{d_{15} \text{ of the filter material}}{d_{85} \text{ of the protected soil (base)}} = \frac{d_{15F}}{d_{85B}} < 5$$

b. $$\frac{d_{50F}}{d_{50B}} < 25$$

c. $$\frac{d_{15F}}{d_{15B}} < 20$$

In order to avoid excessive head loss, the permeability of the filter must be sufficient for the drainage system it protects and:

$$\frac{d_{15F}}{d_{15B}} \geq 5$$

Figure 4-15 illustrates a typical example using these relationships.

These basic criteria can be adjusted to accommodate a base material's coefficient of uniformity (C_u), which is defined as:

$$C_u = \frac{d_{60}}{d_{10}}$$

When the base material has a C_u less than 1.5, the ratio $\frac{d_{15F}}{d_{85B}}$ may be increased to 6. Also, if the C_u of the base material is greater than 4, then $\frac{d_{15F}}{d_{15B}}$ may be increased to 40. Figure 4-16 presents the gradation characteristics of a group of typical filter materials. It is desirable that the gradation curves of the filter and base be roughly "parallel".

Often, a filter that will prevent the migration of the base material's fine soil particles will itself be fine enough to migrate into the underlying coarse material. Therefore, a second filter, or even a series of filters, may be needed to prevent the contamination of the coarse layer or the loss of soil from the base layer (Figure 4-17). The second filter should treat the first filter layer as a base material in its design. Other parameters involved in a filter layer's design are presented in Table 4-9.

To avoid movement of granular filter material through perforations in drainage pipes, the following criteria should be followed.

a. $\frac{d_{85} \text{ of the filter material}}{\text{slot width}} > 1.2$ (slotted pipes)

b. $\frac{d_{85} \text{ of the filter material}}{\text{hole diameter}} > 1.0$ (pipes with circular holes)

4.4.3 Geotextiles

If a geotextile is chosen for use as a filter layer, the following particle-size relationships must be observed:

a. For a geotextile adjacent to a granular material containing 50 percent or less (by weight) of fine (less than 0.074 mm) particles:

FIGURE 4-15

GRANULAR FILTER EXAMPLE (FROM DEPARTMENTS OF THE ARMY AND AIR FORCE, 1979)

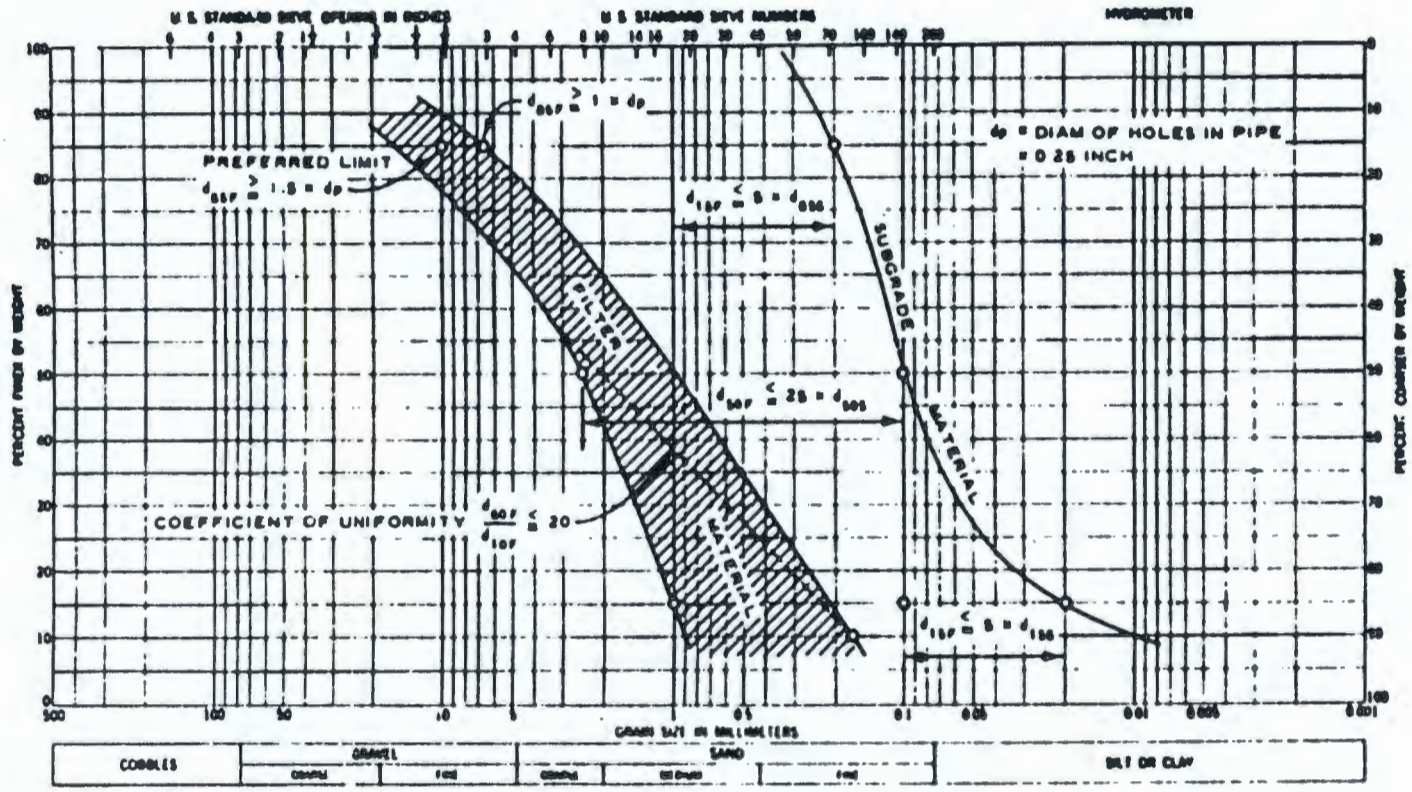

FIGURE 4-16

TYPICAL FILTER MATERIALS (DEPARTMENT OF THE NAVY, 1982)

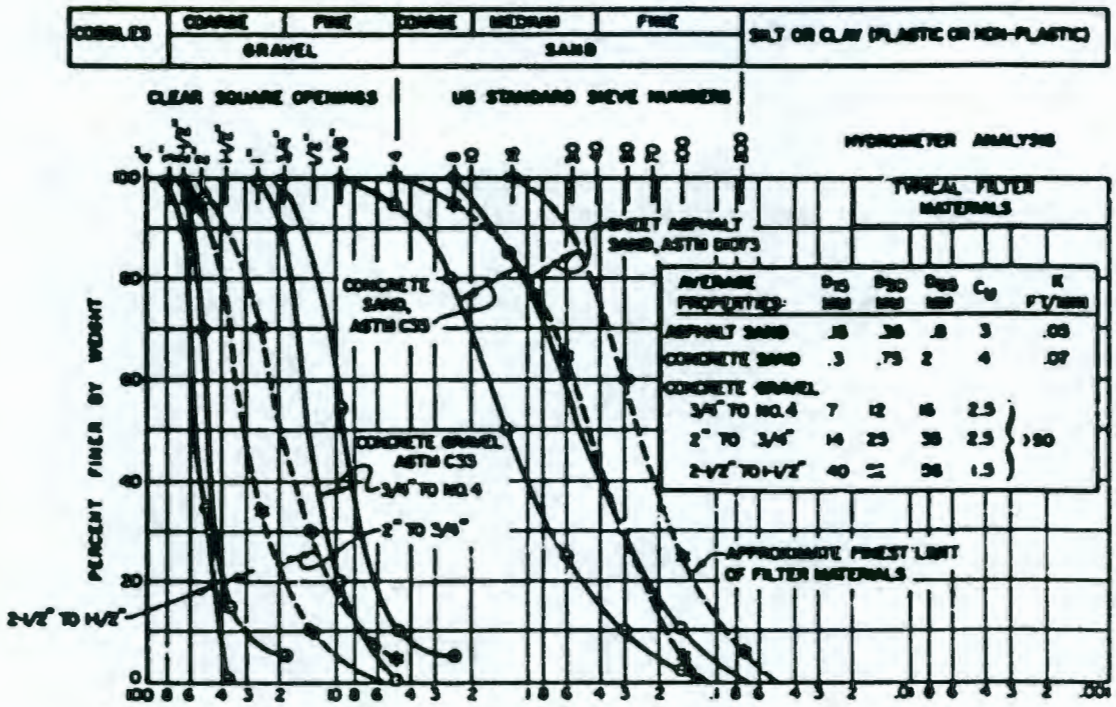

FIGURE 4-17

SERIES OF FILTER LAYERS

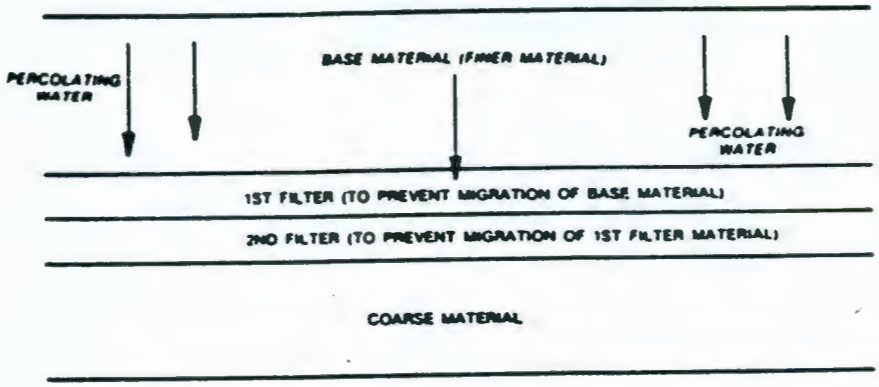

TABLE 4-9

GRANULAR FILTER DESIGN CONSIDERATIONS

a. To avoid internal movement of fines, the filter material should have no more than 5 percent passing the No. 200 sieve.

b. To avoid segregation, a filter should not contain aggregate sizes larger than 3 inches.

c. For dispersive clays, filter tests should be conducted to evaluate the effectiveness of the proposed filter material.

d. A material with a high coefficient of uniformity (C_u) will tend to segregate during placement. Therefore a C_u greater than 20 is usually not desirable.

e. Filter materials should not be skip graded.

$$\frac{d_{85} \text{ base material (mm)}}{\text{E.O.S.* of the geotextile (mm)}} > 1$$

(Total open area of the filter < 36 percent)

b. For a geotextile adjacent to all other soils:

E.O.S. < U.S. Standard Sieve No. 70
(Total open area of the filter < 10 percent)

c. No geotextile should be used with an open area less than 4 percent or an E.O.S. less than U.S. Standard Sieve No. 100.

Table 4-10 presents the designer with a list of conditions to consider when designing a geotextile filter layer.

4.5 Foundation Layer

4.5.1 Function of Foundation Layer

A cover system is only as stable as the foundation it is placed upon. Even the best cover system, placed over a site, cannot withstand the effects

* E.O.S. = equivalent opening size.

TABLE 4-10

GEOTEXTILE FILTER CONSIDERATIONS

a. If gravel is to be placed on a geotextile, the supporting slopes should be 2H:1V or flatter to prevent the gravel from sliding.

b. If large rocks (12 inches or larger) are placed or dumped on a geotextile, sand should be placed above and below the geotextile as needed to protect from tearing.

c. Nonwoven filter cloths, or woven filter cloths with less than 4% open area should not be used where silt is present in sandy soils. A cloth with an equivalent opening size (EOS) equal to the No. 30 sieve and an open area of 36% will retain sands containing silt.

d. When stones are to be dropped directly on the cloth, or where uplift pressure from artesian water may be encountered, the minimum tensile strengths (ASTM D1682, Tests for Breaking Load and Elongation of Textile Fabrics) in the strongest and weakest directions should be not less than 350 and 200 lbs, respectively. Elongation at failure should not exceed 35%. The minimum burst strength should be 520 psi (ASTM D751, Testing Coated Fabrics). Where the cloths are used in applications not requiring high strength or abrasion resistance, the strength requirements may be relaxed.

e. Cloths made of polypropylene, polyvinyl chloride and polyethylene fibers are affected by sunlight, and should be protected from the sun. Materials should be durable against ground pollutants, insect attack, attack by microorganisms, and penetration by burrowing animals.

f. Where filter cloths are used to wrap collection pipes or in similar applications, backfill should consist of clean sands or gravels graded such that the D_{85} is greater than the EOS of the cloth. When trenches are lined with filter cloth, the collection pipe should be separated from the cloth by at least 6 inches of granular material.

g. The absorption of the cloth should not exceed 1% to reduce possibility of fibers swelling and changing EOS and percent of open area.

of massive subsidence within the materials forming its foundation. Although total stabilization of the subsoil and the waste containers buried within it are beyond the scope of this Handbook, the cover designer should be aware of the possibility and consequences of their occurrence.

One of the most common waste containers used over the years has been the 55-gallon steel drum. The contents of drums disposed of at uncontrolled hazardous-waste sites rarely (if ever) received sufficient compaction to ensure that they would not compress appreciably once the container (the drum)

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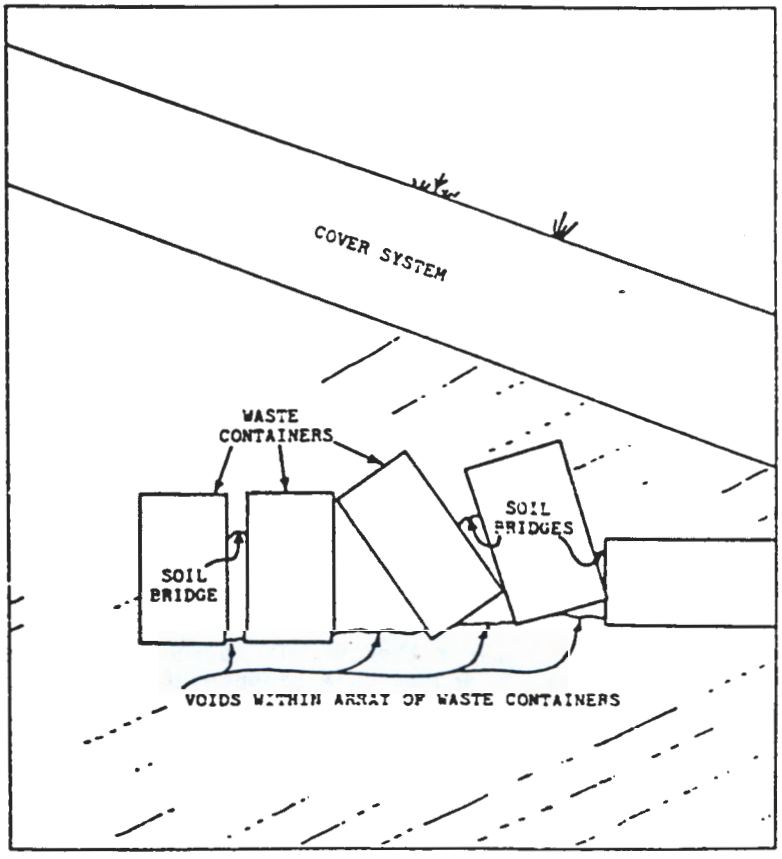
deteriorated. Also, drums were seldom emplaced in a fashion that would minimize the void spaces between them. A normal method of waste emplacement at uncontrolled hazardous waste sites was random dumping. Waste containers were placed in a random fashion, with little effort placed on filling or compacting the voids between the containers. These conditions tend to allow temporary soil bridges to form between containers (Figure 4-18), especially if a cohesive backfill material is used. Subsequently, the voids between the containers provide pathways for water and soil particles to migrate, and the collapse of the soil bridges can cause subsidence of the cover.

FIGURE 4-18

RANDOM DUMPING



Complete stabilization of foundation conditions, i.e., of the wastes and the soils buried with them, falls outside the scope of the cover designer, and in fact techniques for that purpose are still in a developmental stage. The designer's task is to take those realistic steps that will best solve the problem given the current "state of the art." In brief, he can best attack the problem:

- By selection of appropriate soils or other materials.
- By placement and compaction.
- By soil stabilization.

The foundation layer was termed the "buffer" layer by Lutton, Regan, and Jones (1979). The cover designer's goal for a foundation layer is to obtain a stable platform on which to build the rest of his system. The cover designer's challenge resembles that of a highway engineer obliged to build a road across an area of weak, unpredictable, or settlement-prone soils. For this reason, the many excellent discussions in Oglesby (1975) may be useful.

4.5.2 Materials

For most highway purposes, coarse-grained and granular soils are far more satisfactory than fine-grained or plastic soils. The same is true for the foundation layer. See in this connection Table 3-7 in Chapter 3, "Characteristics Pertinent to Roads and Airfields." Those soils rating highly for subgrade or subbase will perform well as foundation-layer soils. This categorization extends to nonsoil residual materials as well; thus crushed slag, mine waste rock, or granular residuals in general should make good foundation-layer materials.

Local conditions, including economic conditions, determine material availabilities. Given this fact, the designer should strive as best he can to call for materials that rate well on Table 3-7 in preference to those that rate poorly. He should remember that the stability of the foundation layer will greatly influence the stability of the entire rest of the cover system throughout its design life.

Another reason for preferring coarse-grained materials is that often the foundation layer will act as the gas-transmission layer. The larger the grain size, the more gas-permeable this layer will be, and the more effectively will this function be carried out.

4.5.3 Compaction

Densification via compaction should be one of the first methods of "soil improvement" considered by a cover designer/contractor faced with an onsite material which, in its present state, is unsuitable foundation material. Compaction should also be the first consideration when dealing with an imported soil whose "as delivered" condition requires improvement in order for it to fulfill the foundation layer's requirements. Since the concepts, design criteria, and general quality assurance surrounding the compaction process are covered in Chapters 3 and 6, this section is concerned with the mechanics of field compaction, with some information dealing with some special

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considerations which should be given to the correlation of the laboratory and field verification testing to the field compaction process.

In the design and construction of the foundation layer, the construction of test sections can be of considerable value to both the cover designer and the construction contractor. A test section is a small section of the cover that is constructed using the specifications generated from laboratory testing or those currently in force. This section can be incorporated into the site's actual cover or it can be constructed elsewhere (such as the borrow area). Test sections aid the designer and contractor by defining the variables associated with field compaction which cannot be adequately or realistically observed in the laboratory. Among the reasons for which a cover designer should consider specifying the construction of a test section are:

- To verify that the compaction procedure yields the desired moisture-density relationship prior to the initiation of an extensive construction effort.
- To determine if the desired moisture-density relationship can be economically obtained in the field.
- To determine if the effects of compaction-related degradation and segregation of the coarse-grained fill would have an adverse effect upon a secondary function of the foundation layer. An example of this would be if a coarse-grained foundation layer would also be expected to serve as a gas collector.
- If the contractor wants to use equipment or a compaction procedure other than that permitted by the specifications.
- If the contractor does not have experience with the material being used in the foundation layer.

Generally, the types of information from a test section include:

- The most effective type and use of equipment for adding and (uniformly) mixing the appropriate amount of water into the soil and compacting it to the desired density.
- The optimum loose lift thickness of the layer to be compacted.
- The required number of passes a compactor must make.
- The ranges of water contents that can be obtained in the field to obtain the desired density for a given compaction process.
- The amount of degradation and segregation that occurs during compaction.
- The physical properties of the compacted material in the field (such as density and grain size distribution).

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Also, the contractor's personnel and the designer's inspectors receive "hands on" experience with the soil.

The design engineers should manage the test section program, although the construction personnel may administer the contract under which the section is constructed. Also, construction control of the test sections should be very strict, or the data may be of questionable value. Methods applicable to the construction and testing of a test section are contained in EM 1110-2-1911, "Construction Control for Earth and Rock-Fill Dams" (Department of the Army, 1977).

The two variables which greatly affect the ease with which a desired density can be obtained are the field compaction effort and the placement water content. The field compaction effort is affected by the contact pressure of the compactor on the soil, the number of passes the compactor makes on the soil, and the lift thickness. Equipment variables which can affect the amount of compactive effort it can apply are:

- For a sheepsfoot roller:

  Drum length and diameter
  Weight (ballasted)
  Arrangement of feet
  Length and face area of feet

- For a rubber-tired roller:

  Tire inflation pressure
  Spacing of tires
  Wheel loads (ballasted)

- For a vibratory roller:

  Static weight
  Imparted dynamic force
  Operating frequency of vibration
  Drum diameter and length

The compaction effort can also be increased by decreasing the lift thickness. Generally, as a rule of thumb, lifts of impervious and semipervious soils are placed in 6- to 8-in. loose thicknesses for a sheepsfoot roller. According to Department of the Army (1977), this thickness can be increased to 9 to 12 in. if the soil is to be compacted with a 50-ton rubber-tired roller. However, the USBR recommends (U. S. Bureau of Reclamation, 1974a) using 8- to 9-in. loose lifts with 12 passes of a 20-ton dual-drum roller. The USBR chose this guidance because they feel that the laboratory standard which they use for control (ASTM D-698) has the same intensity of effort. Table 3-7 provides general guidance as to the compaction equipment requirements for different types of soils. Usually the standard density desired in a compacted soil ranges from 90 to 95 percent Standard Proctor.

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As discussed in Chapter 3, when the water content for a certain soil under a given compactive effort deviates from optimum, the densities obtained will be less than the maximum obtainable. For a soil at a water content less than optimum, an increase in the compactive effort will generally increase the soil's density. However, a soil with a water content considerably greater than optimum will tend to shear under increased compactive effort rather than compact.

The thickness of the foundation layer will usually be controlled by:

- The distance the designer or contractor wishes to maintain between his personnel and machinery and the site's surface (especially if the surface is contaminated).
- The irregularities (gullies and hills) which must be overcome to obtain a good working surface.
- The bearing capacity of the foundation layer material itself.
- The amount of compaction pressure the designer wishes to impose upon the site's original surface.

The first two factors are site-specific and will have to be addressed according to the site's degree of surface contamination and topography as well as the requirements imposed on the contractor in relation to worker safety and equipment decontamination. A bearing-capacity failure occurs when the shear strength of the soil is exceeded. Since the computation of bearing capacity can be a complex operation and highly dependent upon material characteristics, only a qualified geotechnical engineer should attempt it. Information concerning shear-strength determination, ultimate and allowable bearing capacity, and how these correlate to fine- and coarse-grained materials can be obtained in Peck, Hanson, and Thornburn (1974), Department of the Navy (1971), and Departments of the Army and Air Force (1982). The last factor may arise when the designer may not wish the compaction machinery to disturb or shear the site's original surface while it compacts the foundation layer's first lift. The problem can usually be remedied by increasing the lift thickness or decreasing the weight of the machinery. However, the designer should be mindful that this remedy will cause an increase in the number of passes required. Table 4-11 lists typical properties of compacted soil materials.

4.5.4 Soil Stabilization

As mentioned in Section 3.3, the primary soil-stabilizing additives are cement, lime, fly ash, and bituminous materials. Choosing between these additives will have to be done on a case-by-case basis as their suitability, availability, and cost vary with the different soil types and geographical regions. However, there are tests which are used on all additive-stabilized mixtures which yield many of the design characteristics of the mixture. These tests and parameters are found in Table 4-12.

TABLE 4-11

TYPICAL PROPERTIES OF COMPACTED MATERIALS

Group symbol	Soil type	Range of maximum dry unit weight, pcf	Range of optimum moisture, percent	Typical value of compression: At 1.4 tsf (20 psi) percent of original height	Typical value of compression: At 3.6 tsf (50 psi) percent of original height	Typical strength characteristics: Cohesion (as compacted) psf	Cohesion (saturated) psf	Φ (effective stress envelope) degrees	Tan Φ	Typical coefficient of permeability ft/min.	Range of CBR values	Range of subgrade modulus k lb/cu in.
GW	Well graded clean gravels gravel-sand mixtures	125-135	11-8	0.3	0.6	0	0	>38	>0.79	5×10^{-2}	40-80	300-500
GP	Poorly graded clean gravels, gravel-sand mix	115-125	14-11	0.4	0.9	0	0	>37	>0.74	10^{-1}	30-60	250-400
GM	Silty gravels, poorly graded gravel-sand-silt	120-135	12-8	0.5	1.1	--	--	>34	>0.67	$>10^{-6}$	20-60	100-400
GC	Clayey gravels, poorly graded gravel-sand-clay	115-130	14-9	0.7	1.6	--	--	>31	>0.60	$>10^{-7}$	20-40	100-300
SW	Well graded clean sands, gravelly sands	110-130	16-9	0.6	1.2	0	0	38	0.79	$>10^{-3}$	20-40	200-300
SP	Poorly graded clean sands, sand-gravel mix	100-120	21-12	0.8	1.4	0	0	37	0.74	$>10^{-3}$	10-40	200-300
SM	Silty sands, poorly graded sand-silt mix	110-125	16-11	0.8	1.6	1050	420	34	0.67	5×10^{-5}	10-40	100-300
SM-SC	Sand-silt clay mix with slightly plastic fines	110-130	15-11	0.8	1.4	1050	300	33	0.66	2×10^{-6}	--	
SC	Clayey sands, poorly graded sand-clay mix	105-125	9-11	1.1	2.2	1550	230	31	0.60	5×10^{-7}	5-20	100-300
ML	Inorganic silts and clayey silts	95-120	24-12	0.9	1.7	1400	190	32	0.62	10^{-5}	15 or less	100-200
ML-CL	Mixture of inorganic silt and clay	100-120	22-12	1.0	2.2	1350	460	32	0.62	5×10^{-7}	--	
CL	Inorganic clays of low to med. plasticity	95-120	24-12	1.3	2.5	1800	270	28	0.54	10^{-7}	15 or less	50-200
OL	Organic silts and silt-clays, low plasticity	80-100	33-21	--	--	--	--	--	--	--	5 or less	50-100
MH	Inorganic clayey silts, elastic silts	70-95	40-24	2.8	3.8	1500	420	25	0.47	5×10^{-7}	10 or less	50-100
CH	Inorganic clays of high plasticity	75-105	36-19	2.6	3.9	2150	230	19	0.35	10^{-7}	15 or less	50-150
OH	Organic clays and silty clays	65-100	45-21	--	--	--	--	--	--	--	5 or less	25-100

Notes:

1. All properties are for condition of "standard Proctor" maximum density, except values of k and CBR which are for "modified Proctor" maximum density.
2. Typical strength characteristics are for effective strength envelopes and are obtained from USBR data.
3. Compression values are for vertical loading with complete lateral confinement.
4. (>) indicates that typical property is greater than the value shown.
   (--) indicates insufficient data available for an estimate.

Source: Department of the Navy (1971)

TABLE 4-12

TESTS FOR STABILIZED SOILS

Design Parameter	Test Designation	Title
Additive Requirement	Found in TM 5-822-4/AFM 88-7, Chap. 4/NAVFAC DM21.5 (Dept. of the Army, Air Force, and Navy, 1982)	
Unconfined Compressive Strength	ASTM D-1633	Compressive Strength of Molded Soil-Cement Cylinders
Wet-Dry Characteristics	ASTM D-559	Wetting-and-Drying Tests of Compacted Soil-Cement Mixtures
Freeze-Thaw Characteristics	ASTM D-560	Freezing-and-Thawing Tests of Compacted Soil-Cement Mixtures
Swell Characteristics	MIL-STD-621A	
Moisture Density Relationship	ASTM D-558	Moisture-Density Relations of Soil-Cement Mixtures
Plasticity Index of Mixture	ASTM D-423 ASTM D-424	Liquid Limit of Soils Plastic Limit and Plasticity Index of Soils

Recommended sources of information on soil stabilization are "A Basic Asphalt Emulsion Manual" (Asphalt Institute, 1979), "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982), and McDowell (1972). In addition, the reader may wish to consult discussions of stabilized soils and their applications in the Earth Manual (U. S. Bureau of Reclamation, 1974b) and Oglesby (1975).

4.5.4.1 Cement Stabilization

Table 4-13 presents guidance for estimating cement requirements for various soils and Figure 4-19 and Tables 4-14 through 4-16 present information required in the design process. Steps in this process are as follows:

- Select an estimated cement content from Table 4-13 according to soil classification, or, through testing, determine the minimum cement content required to obtain the desired PI of the soil.

TABLE 4-13

ESTIMATED CEMENT REQUIREMENTS FOR VARIOUS SOIL TYPES

Soil Classification[a]	Initial Estimated Cement Requirement Percent Dry Weight
GW-SW	5
GP, SW-SM, SW-SC, SW-GM, SW-GC	6
GM, SM, GC, SC, SP-SM, SP-SC, GP-GM, GP-GC, SM-SC, GM-GC	7
SP, CL, ML, ML-CL	10
MH, OH	11
CH	10

[a]Soil classification corresponds to MIL-STD-619B.

Source: "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982)

TABLE 4-14

AVERAGE CEMENT REQUIREMENTS FOR GRANULAR AND SANDY SOILS

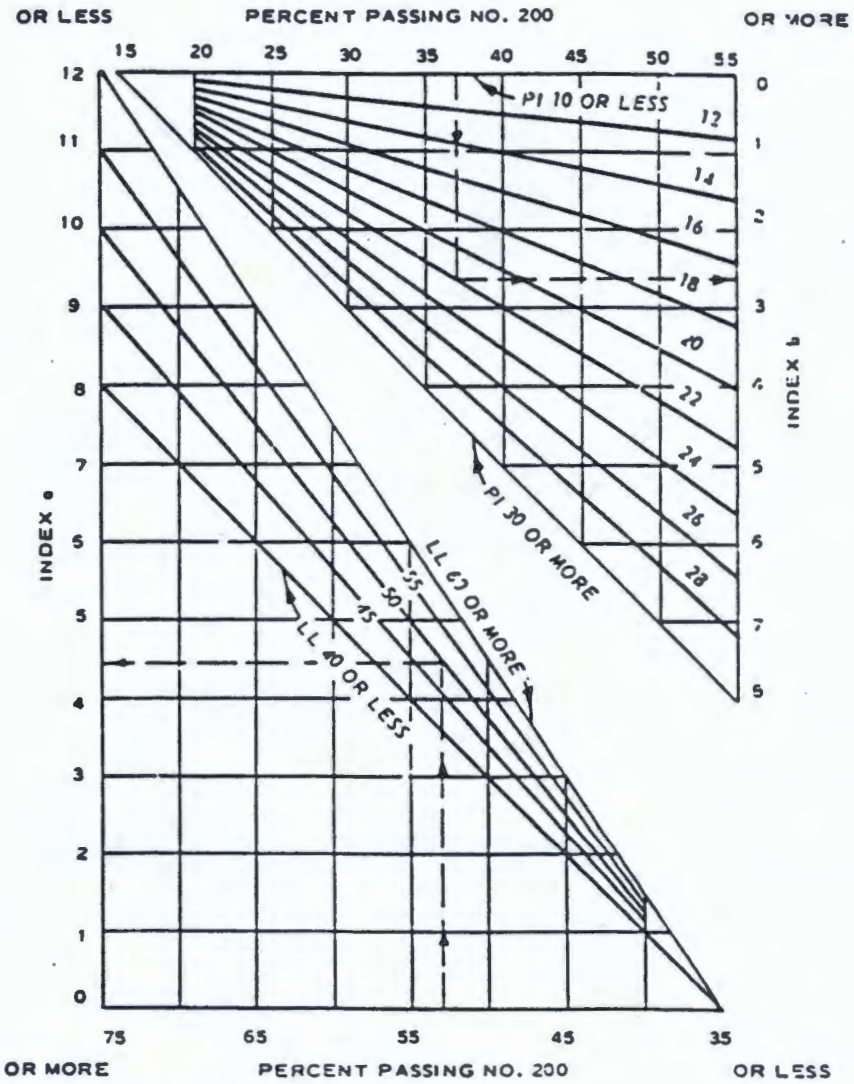
Material Retained on No. 4 Sieve percent	Material Smaller Than 0.05 mm percent	Cement Content, Percent by Weight Maximum Dry Density, lb/cu ft (Treated Material)					
		116-120	121-126	127-131	132-137	138-142	143 or more
0-14	0-19	10	9	8	7	6	5
	20-39	9	8	7	7	5	5
	40-50	11	10	9	8	6	5
15-29	0-19	10	9	8	6	5	5
	20-39	9	8	7	6	6	5
	40-50	12	10	9	8	7	6
30-45	0-19	10	8	7	6	5	5
	20-39	11	9	8	7	6	5
	40-50	12	11	10	9	8	6

Note: Base course goes to 70 percent retained on the No. 4 sieve.

Source: "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982)

FIGURE 4-19

GROUP INDEX FOR SOIL-CEMENT MIXTURES



NOTE: GROUP INDEX = INDEX a + INDEX b.

(Reprinted from Soil-Cement Laboratory Handbook (EB052.04S) with permission of the Portland Cement Association, Skokie, Illinois.)

TABLE 4-15

AVERAGE CEMENT REQUIREMENTS FOR SILTY AND CLAYEY SOILS

Group Index[a]	Material Between 0.05 and 0.005 mm percent	Cement Content, Percent by Weight — Maximum Dry Density, lb/cu ft (Treated Material)						
		99-104	105-109	110-115	116-120	121-126	127-131	132 or more
0-3	0-19	12	11	10	8	8	7	7
	20-39	12	11	10	9	8	8	7
	40-59	13	12	11	9	9	8	8
	60 or more	-	--	--	--	--	--	--
3-7	0-19	13	12	11	9	8	7	7
	20-39	13	12	11	10	9	8	8
	40-59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
7-11	0-19	14	13	11	10	9	8	8
	20-39	15	14	11	10	9	9	9
	40-59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
11-15	0-19	15	14	13	12	11	9	9
	20-39	16	15	13	12	11	10	10
	40-59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
15-20	0-19	17	16	14	13	12	11	10
	20-39	18	17	15	14	13	11	11
	40-59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

[a]Taken from Figure 4-19.

Source: "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982)

TABLE 4-16

DURABILITY REQUIREMENTS

Type of Soil Stabilized[a]	Maximum Allowable Weight Loss After 12 Wet-Dry or Freeze-Thaw Cycles Percent of Initial Specimen Weight	
	Army and Air Force	Navy
Granular, PI $\leq$ 10	11	14
Granular, PI $\leq$ 10	8	14
Silt	8	14
Clays	6	14

[a]Refer to MIL-STD-619B and MIL-STD-621A

- Determine moisture-density relationship of soil-cement mixture.

- Vary the cement content until the values obtained in the test are within ± 2 percent of that shown in Tables 4-14 or 4-15.

- Perform unconfined compression test to ascertain that mixture will support cover/construction loads. The Army and Air Force recommend a minimum (unconfined) compressive strength of 250 psi, while the Navy recommends 300 psi for cement, and 150 psi for lime, stabilization of a subgrade/subbase material beneath a flexible pavement.

- Perform wet-dry and freeze-thaw testing and compare with values in Table 4-16.

4.5.4.2 Lime or Lime-Based Stabilization

Lime, lime-cement, and lime/cement/fly-ash require the same type of trial-and-error procedure, which varies in the testing requirements for the lime content (which is pH based) and the additional testing required for fly-ash quality (ASTM C593). The preferred method of determining the initial design lime content is to prepare several mixtures and determine the pH of each. The lowest lime content producing the highest pH is the initial design lime content with which to begin the moisture-density, strength and durability testing.

4.5.4.3 Bituminous Stabilization

Generally, bituminous materials work best in coarse-grained soils, as their effectiveness is directly related to the degree of penetration or homogeneity they attain in the soil mass. Table 4-17 provides recommended ranges

TABLE 4-17

RECOMMENDED GRADATIONS FOR BITUMINOUS-STABILIZED SUBGRADE MATERIALS

Sieve Size	Percent Passing
3 in.	100
No. 4	50-100
No. 30	38-100
No. 200	2-30

Source: "Soil Stabilization for Pavements" (Departments of the Army, Air Force, and Navy, 1982)

of gradation for bituminous-stabilized subgrade materials. These ranges can be regarded as applicable when considering bituminous stabilization of the foundation layer. Table 4-18 provides guidance as to which asphalt grades are applicable to which aggregate gradation.

TABLE 4-18

ASPHALT AGGREGATE GUIDANCE

1. Open Graded Aggregate	RC-250, RC-800, MC 3000, MS-2, and CMS-2
2. Well Graded Aggregate with Little or No Material Passing the No. 200 Sieve	RC-250, RC-800, MC-250, MC-800, MS-2, CMS-2, SS-1, CSS-1
3. Aggregate with a Considerable Percentage of Fine Aggregate and Material Passing No. 200 Sieve	MC-250, MC-800, SC-250, SC-800, SS-1, SS-1h, CSS-1, CSS-1h, MS-2, CMS-2

RC = Rapid Curing
MC = Medium Curing
SC = Slow Curing
MS = Medium Setting
SS = Slow Setting
CMS = Medium Setting Emulsions
CSS = Slow Setting Emulsions

4.6 Hydraulic Barrier Layer

4.6.1 General

The primary function of the hydraulic barrier is to divert or impede the downward percolation of any water coming into contact with it. The ability of this layer to perform its function is critical to the success of the cover system. The hydraulic barrier constitutes the primary and final impediment to the passage of any water percolating down from the upper layers of the cover system. Therefore, the designer should require a high degree of confidence in the methods and materials used in the design and construction of this layer, as its failure will represent a major reduction in the efficiency of the cover system.

The materials being considered and used in cover systems at waste sites are largely the same materials that have been used as liners for waste impoundments and solid waste landfills. Although the initial design procedures are alike or similar, the conditions which must be designed against, as well

9 3 1 2 9 0 4 1 0 8 0

as the consequences of imperfections in the hydraulic barrier, differ between covers and liners. The hydraulic barrier in a cover system should not experience the hydraulic head (depth of water over the barrier) that an impoundment liner would. By and large, the cover barrier will be exposed only to water, while the liner is exposed to whatever chemicals are at the site. Also, the length of time that the overlying soil layer will remain in a saturated condition will be much less for a cover system than a liner. Consequently, the amount of leakage due to pinholes, cracks, or other minute avenues through the hydraulic barrier in a cover system will generally be less than through a liner at the same site.

The severity of the problem represented by such leakage will depend upon the amount the designer decides is tolerable for the site and the consequences the leakage would have upon the stability of the cover system as a whole. Particular attention should be paid to the consequences of leakage through the hydraulic barrier where the in situ soils beneath the wastes (which provide the support for the cover system) are of a collapsible nature. Leakage can also have a detrimental effect if the soils are prone to swelling or heaving from frost action. However, as discussed in section 4.11, the latter will probably not be a problem in a well-designed cover system, and swelling is not generally a problem if the overlying load is sufficient, thus if the cover system as a whole is thick enough. Heaving will be a major consideration where more brittle materials (asphalt concrete and soil-cement) are used as barrier materials.

4.6.2 Failure Mechanisms

There are three primary failure mechanisms which the hydraulic barrier materials might undergo: chemical, mechanical, and environmental.

4.6.2.1 Chemical

As previously mentioned in Chapter 3, "Nonsoil Materials," if the hydraulic barrier material is to be placed in a zone where it will make contact with the chemicals disposed of at the site, then chemical compatibility testing of the material must be performed. Table 4-19 presents guidance on a variety of materials and their compatibility with some general types of chemical wastes. However, as the composition and concentration of the chemicals which might be encountered at a Superfund site could vary considerably from site to site, the designer should, if possible, rely on laboratory testing results rather than general product guidance.

4.6.2.2 Mechanical

Mechanical failure encompasses the stresses which the hydraulic barrier material may undergo during its installation and service in the field. Some of the more general causes of mechanical failure are:

TABLE 4-19

CHEMICAL COMPATIBILITY GUIDANCE[a]

Substance	Type of Lining									
	PE	Hypalon	PVC	Butyl Rubber	Neoprene	Asphalt Panels	Asphalt Concrete	Concrete	CPE	3110
Animals oils	OK[b]	OK	ST	OK	OK	Q	Q	NR	OK	OK
Petroleum oils (no aromatics)	OK[b]	Q	NR	NR	SW	NR	NR	OK	OK	OK
Domestic sewage	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Salt solutions	OK	OK	OK	OK	OK	OK	Q	NR	OK	OK
Base solutions	OK	OK	OK	OK	OK	OK	OK	Q	OK	OK
Mild acids	OK	OK	OK	OK	OK	OK	OK	NR	OK	OK
Oxidizing acids	NR	NR	NR	NR	Q	NR	NR	NR	NR	NR
Petroleum oils	Q	NR	NR	NR	NR	NR	NR	OK	NR	NR

[a]Adapted from Kays (1977). For details of pertinent compatibility testing, see Haxo et al. (1980, 1983) and August et al. (1984).

[b]Must be a one-piece lining

OK = Generally Satisfactory
Q = Questionable
NR = Not Recommended
ST = Stiffens
SW = Swells

- Tearing or cracking of the material due to impact from construction equipment (Figure 4-20(a)).
- Tensile stresses generated by being placed on too steep a slope (Figure 4-20(b)).
- Tensile stresses resulting from subsidence of the underlying foundation (Figure 4-20(c)).
- Intrusion of particles from an upper or lower coarse-grained layer into hydraulic barrier (Figures 4-20(d-e)).
- Puncturing or cracking the material by compacting or operating over it with an inadequate protective layer (Figure 4-20(f)).

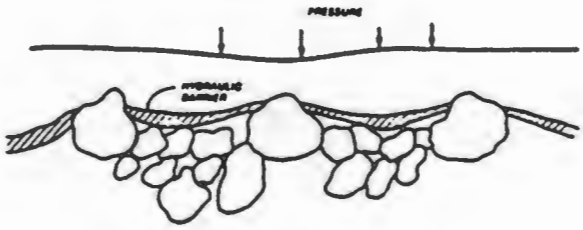
Realistically, mechanical failure is probably a much greater threat than chemical failure. An important element in guarding against it is high-quality inspection during construction (see Chapter 6). If a polymeric membrane is used, it should be one with high elongation. The thinner the barrier, the greater is the threat of mechanical failure. A thick barrier of compacted soil, while not completely impervious, will be much more inherently durable and resistant to mechanical failure than a barrier consisting of a single thin membrane or member.

9 3 1 2 9 0 4 1 0 8 2

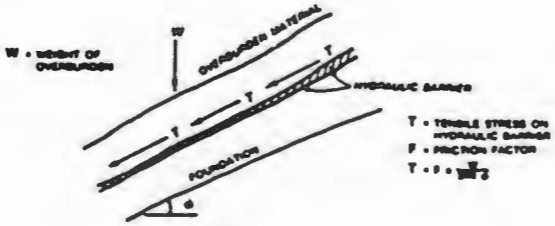
FIGURE 4-20

TYPES OF MECHANICAL FAILURES

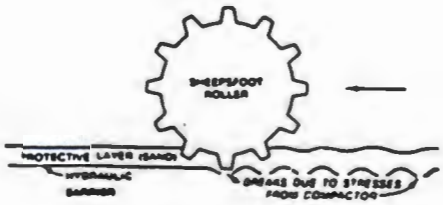
a. CONSTRUCTION MACHINERY DAMAGE



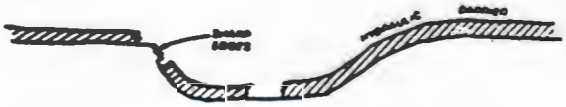
b. COARSE MATERIAL PUNCTURES HYDRAULIC BARRIER FROM UNDERNEATH



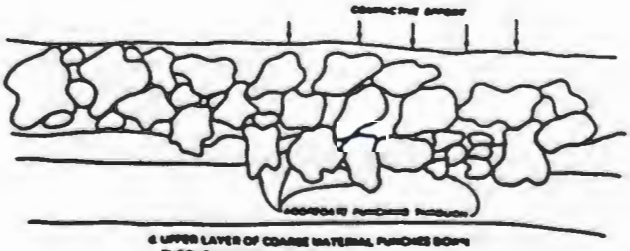
c. TENSILE STRESS GENERATED BY OVERBURDEN AND DEGREE OF SLOPE (α)



d. INSUFFICIENT PROTECTIVE LAYER



e. SUBSIDENCE



f. UPPER LAYER OF COARSE MATERIAL PUNCHES DOWN THROUGH HYDRAULIC BARRIER

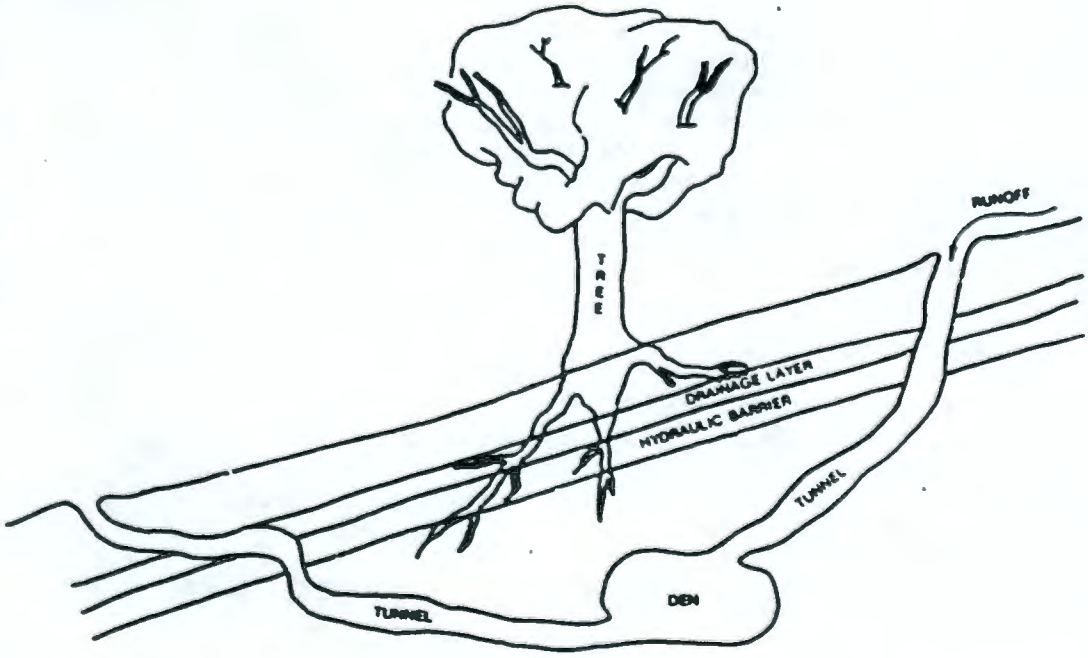
4.6.2.3 Environmental

Environmental failure mechanisms involve damage from weathering, burrowing animals, and plant roots. The weathering process does not solely consist of direct exposure to the elements (wind, rain, sunlight, snow, etc.). Since, in almost all cases, the hydrauiic barrier will be covered as quickly as possible, the designer should consider the effects of freeze-thaw cycles (especially if the barrier is above the frost depth), the effects of the cycles of wetting and drying occurring in the soil as well as how long it remains wet, and the natural chemical nature of the soil. All these elements combine to "weather" the barrier.

Burrowing animals and plant roots are a great danger to the cover system as a whole and to the hydraulic barrier in particular. Although the more rigid materials like soil-cement and asphalt concrete are more resistant to attack, they are not completely immune. A burrowing animal can do extensive damage. For example, a badger can leave a maze of 6 to 8-in.-diam tunnels through a cover system (Figure 4-21). This provides surface water with an avenue of infiltration, and the burrowing animals bring contaminated soil and debris to the surface during their digging. Plant roots can clog a drainage system and penetrate the hydraulic barrier, leaving avenues for infiltration when the tree or plant dies (Figure 4-21).

FIGURE 4-21

BIOTIC INTRUSION



9 3 1 2 9 0 4 1 0 8 4

Methods to combat the threat of environmental failure are discussed in section 4.8 "Biotic Barrier."

4.6.3 Barrier Materials

Materials suitable for use as hydraulic barriers were discussed in Chapter 3. These materials can be categorized as follows:

- Soils
- Soils amended with additives
- Nonsoil materials

4.6.3.1 Soils

The materials usually first considered for use in any element of a cover system are the soils that are found onsite or that can be imported from a local source. As shown in Table 4-20 and as discussed in Chapter 3, permeabilities vary from soil type to soil type. Tables 3-7, 3-8, and 3-9, and the accompanying text, should make clear these types of soils that are applicable as a hydraulic barrier. The expected percolation performance of a soil barrier system may be predicted using one of the water-balance methods discussed in section 4.2.

It is most important that a soil barrier layer be thoroughly compacted. Compaction of at least 95 pct of Standard Proctor maximum density should be called for in all cases. Except with heavy clays, it is difficult to overcompact. Heavy clays compacted at optimum moisture content may swell if more moisture becomes available. They should, therefore, be compacted wet of optimum (Oglesby, 1975, p 448). In fact, any given soil will be more impermeable compacted wet of, rather than at, optimum moisture content. Too much moisture, however, may lead to "pumping" of the soil. The judgment of an experienced field engineer is probably the best guide.

4.6.3.2 Amended Soils

The modification of soils using additives was discussed in Chapter 3. One of the most commonly used additives for the purpose of reducing permeability is sodium bentonite. Table 4-21 affords the designer some guidance as to application rates, but the amount of bentonite that is required should be determined by a program of laboratory testing. The following variables should be investigated as to their impact upon the coefficient of permeability of the amended soil:

TABLE 4-20

SOIL PERMEABILITY GUIDANCE

Coefficient of Permeability k in cm per sec (log scale)

10^2 | 10^1 | 1.0 | 10^{-1} | 10^{-2} | 10^{-3} | 10^{-4} | 10^{-5} | 10^{-6} | 10^{-7} | 10^{-8} | 10^{-9}

Drainage	Good			Poor	Practically Impervious
Soil types	Clean gravel	Clean sands, clean sand and gravel mixtures	Very fine sands, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified clay deposits, etc.		"Impervious" soils, e.g., homogeneous clays below zone of weathering
			"Impervious" soils modified by effects of vegetation and weathering		
Direct determination of k	Direct testing of soil in its original position—pumping tests. Reliable if properly conducted. Considerable experience required				
	Constant-head permeameter. Little experience required				
Indirect determination of k		Falling-head permeameter. Reliable. Little experience required	Falling-head permeameter. Unreliable. Much experience required	Falling-head permeameter. Fairly reliable. Considerable experience necessary	
	Computation from grain-size distribution. Applicable only to clean cohesionless sands and gravels				Computation based on results of consolidation tests. Reliable. Considerable experience required

Source: Terzaghi and Peck (1967)

TABLE 4-21

SOIL CONSERVATION SERVICE RECOMMENDED SODIUM BENTONITE APPLICATION RATE FOR FARM PONDS

Soil	Application Method	Application Rate psf
Clay	Pure membrane or mixed layer	1.0-1.5
Sandy silt	Mixed layer	1.0-1.5
Silty sand	Mixed layer	1.5-2.0
Clean sand	Mixed layer	2.0-2.5
Open rock or gravel	Clay or sand mixed layer	2.5-3.0

Source: Lutton, Regan, and Jones (1979)

9 3 1 2 9 0 4 1 0 8 6

- Type of soil (which is to be amended).
- Type of bentonite.
- Quality of bentonite.
- Water content.
- Density.
- Thickness.

The required application rate, layer thickness, and degree of compaction (usually 95 percent Standard Proctor) can be derived from this testing program. The most common method of constructing a soil-bentonite mixture is to spray or dump the bentonite to a desired thickness over the soil, disk it into the soil to the desired depth, adjust the water content (by spraying water on it or allowing it to air dry), and compact it to the desired density. This in-place mixing is usually good for a layer of 6 to 8 in. in thickness. If a thicker barrier is specified, then the lower lift (layer) should be scarified and another layer constructed over it.

It should be remembered that bentonite, because it contains highly active clay minerals, is very subject to chemical attack.

Another type of barrier is a bentonite membrane. This differs from the soil-bentonite barrier in that it is composed solely of bentonite or the bentonite is not mechanically mixed into the soil. Two typical methods are:

- A suspension of bentonite in water (usually 0.05 percent of the water's weight) is sprayed over the area to be sealed. Application rates vary with the soil type and texture.
- The same bentonite suspension as above is sprayed over a gravel or sand bed (usually 6 in. thick). The bentonite settles through this layer and seals the voids.

The bentonite-gravel/sand layer provides a stronger and more durable layer, but this type of layer should not be used on a steep slope (usually 2H:1V is considered the maximum).

Some states (Washington and Minnesota, for example) have regulations governing the design and construction of bentonite liners for waste lagoons. Although these regulations may be too conservative for cover design they will provide valuable design insight for that state and may dicate (by law) the minimum physical standards that any hydraulic barrier used at a waste disposal site must meet.

Polymeric sealants have also been used to form hydraulic barriers under waste ponds (Middlebrooks et al., 1978). The barrier consists of alternatingly sprayed layers of polymer and bentonite. This type of barrier is supposedly

more resistant to chemical attack including the calcium-sodium exchange phenomenon.

Another hydraulic barrier employing an additive amended soil is a layer of soil-cement. The following lab tests should be performed to determine the proper cement content, optimum moisture content, and maximum density of the soil-cement mixture:

- ASTM D558 - Moisture Density Test
- ASTM D559 - Wet Dry Test
- ASTM D560 - Freeze Thaw Test

The amount of cement to be used in the mixture depends very much upon the type of soil to be amended. Table 4-22 presents some examples of some soils that have been used by the Portland Cement Association in a program of laboratory permeability testing. A point that stands out is that they are all sands. Soil-cement performs better in coarse-grained material as it is easier to mix the cement with this type of material to obtain a homogeneous mix.

4.6.3.3 Asphalt

The various forms asphalt may assume in its applications as a hydraulic barrier include:

- Surface treatments.
- Asphalt membrane.
- Asphalt concrete.

A surface treatment may be a hot asphalt, asphalt emulsion, or asphalt mastic material (hot asphalt and a mineral filler) sprayed over a prepared surface to make it more watertight. A surface seal is normally used to fill and seal small cracks that might form in the more rigid liners like soil cement and asphalt concrete. It could be considered as a hydraulic barrier by itself but extreme caution must be utilized during construction of the subsequent cover layers due to the thinness of the seal (punctures easily).

Table 4-23 presents requirements for the asphalt used in hydraulic barrier construction. Table 4-24 presents guidance for emulsified asphalt.

An asphalt membrane consists of hot asphalt which is sprayed directly upon the foundation in a sufficient thickness so that it may act as a hydraulic barrier by itself (not as just a seal coat). Table 4-25 presents general guidance as to the general characteristics and testing requirements for a hot asphalt membrane.

9 3 1 2 9 0 4 1 0 8 8

TABLE 4-22

PERMEABILITY OF CEMENT-TREATED SOILS

Soil Number or Sample Identification	Dry Density, pcf	Moisture Content, Percent	Cement Content Percent by Volume	Type of Soil-cement	K, Coefficient of Permeability, ft per year	USDA Texture	Gradation Analysis, Percent Passing 3/4	4	10	40	200	.05	.005	AASHTO Soil Class[a]	Cement Requirement by Volume[b]
Standard Ottawa sand	108.2	10.8	0	Compacted	48,750	Coarse sand	(100% pass #20; 0% pass # 30)							A-1-b(0)	--
	112.8	9.4	5.7	Compacted	6,940										
	117.6	9.7	11.3	Compacted	76.1										
SP soil, Il N-26 Idaho	--	--	0	Plastic	2,460	Sand	100	99	98	73	9	8	3	A-3(0)	--
	98.6	24.1	8	Plastic	130										
	99.8	20.1	8	Plastic	130										
	100.3	18.8	20	Plastic	0.8										
Graded Ottawa sand	103.2	13.7	0	Compacted	16,300	Sand	100	100	100	#50	#100	--	--	A-1-a(0)	--
	104.7	13.6	5.3	Compacted	473					28	2				
	107.4	12.3	10.3	Compacted	21.4										
PCA soil No. 7018 Florida	101.0	12.2	0	Compacted	746	Sand	100	100	100	91	7	1	--	A-3(0)	10.0
	100.9	13.3	3.1	Compacted	562										
	103.6	12.3	6.3	Compacted	192										
	105.3	12.0	9.2	Compacted	21.1										
PCA soil No. S-2 Illinois	100.8	14.9	0	Compacted	4,960	Fine sand	100	100	100	96	13	12	2	A-2-4(0)	8.0
	99.9	14.7	3.1	Compacted	1,359										
	104.0	15.1	6.3	Compacted	59.5										
	104.8	15.1	9.2	Compacted	11.5										
PCA soil No. 6998 Maine	104.8	10.6	0	Compacted	2,400	Coarse sand	100	100	96	51	5	2	--	A-3(0)	7.0
	107.2	9.5	3.3	Compacted	651										
	111.7	10.3	6.8	Compacted	36.2										
	113.4	10.2	9.9	Compacted	7.6										
PCA soil No. 6863-2 Maryland	104.9	10.3	0	Compacted	1,640	Sand	100	100	100	77	4	--	--	A-3(0)	8.5
	106.6	10.8	3.3	Compacted	90.3										
	112.4	10.3	6.8	Compacted	25.6										
	114.4	10.3	10	Compacted	3.6										
SP sand, Il N-265 Utah	100.1	16.0	0	Compacted	356	Fine sand	100	99	99	96	6	6	1	A-3(0)	--
	105.8	14.8	6	Compacted	19.8										
	109.3	13.5	12	Compacted	1.1										
PCA soil No. 7019 Florida	101.0	13.8	0	Compacted	144	Fine sand	100	100	100	94	2	--	--	A-3(0)	11.0
	104.7	13.3	3.1	Compacted	33										
	106.2	13.4	6.5	Compacted	0.3										
	108.8	13.4	9.5	Compacted	0.02										

[a] All soils nonplastic.
[b] Cement requirement based on ASTM Standard Freeze Thaw and Wet-Dry Tests for Soil-Cement Mixtures and PCA Paving Criteria.

Source: Portland Cement Association's Soil-Cement Information Bulletin IS173..W

TABLE 4-23

REQUIREMENTS FOR ASPHALT FOR USE IN WATERPROOF MEMBRANE CONSTRUCTION (ASTM D-2521)

Softening point (ring and ball),	79° to 93°C (175° to 200°F)
Penetration of original sample:	
At 25°C (77°F), 100 g, 5 s	50 to 60
At 0°C (32°F), 200 g, 60 s	30 min
At 46°C (115°F), 50 g, 5 s	120 max
Ductility at 25°C (77°F) cm	3.5 min
Flash point (Cleveland open cup)	218°C (425°F) min
Solubility in carbon tetrachloride, %	97.0 min
Loss on heating, %	1.0 max
Penetration at 25°C (77°F) after loss on heating, % of original	60 min

Source: Asphalt Institute (1976)

TABLE 4-24

SELECTION OF EMULSIFIED ASPHALT AMOUNT

Type	Approximate Emulsified Asphalt Content, Percent by Weight of Aggregate[a]
Processed Dense Graded	5.0-10.0
Sands Silty Sands Semi-Processed Crusher Pit or Bank Run	4.5-8.0
Open Graded	
Coarse	4.5-6.5
Medium	5.0-7.0
Fine	6.0-8.0

[a]With porous aggregates the emulsified asphalt content should be increased by a factor of approximately 1.2. Porous aggregates are those which absorb more than 2 percent water by dry weight when tested by ASTM Method C 127.

Source: Asphalt Institute (1979)

TABLE 4-25

ASPHALT TESTING GUIDANCE

Characteristics	ASTM Test Method	AASHO Test Method	Limits, ASTM D2521
Softening Point (Ring and Ball), °F.	D36	T53	175-200
Penetration of Original Sample:			
At 32°F., 200 g., 60 sec.			30+
At 77°F., 100 g., 5 sec.	D5	T49	50-60
At 115°F., 50 g., 5 sec.			120-
Ductility at 77°F., cms.	D113	T51	3.5+
Flash Point (Cleveland Open Cup), °F.	D92	T48	425+
Solubility in Carbon Tetrachloride, %	D4[a]	T44[a]	97.0+
Loss on Heating, %	D6	T47	1.0-
Penetration After Loss on Heating, % of Original	D5	T49	60+

General Requirements: The asphalt shall be prepared by the refining of petroleum. It shall be uniform in character and shall not foam when heated to 400°F.

[a]Except that carbon tetrachloride is used instead of carbon disulphide as solvent, Method No. 1 in AASHO Method T44, or Procedure No. 1 in ASTM Method D4.

Source: The Asphalt Institute

Asphalt membranes formed of asphalt cement or emulsified asphalt are usually sprayed over the ground surface at a rate of 0.25 gal/yd^2 (1 liter/m^2) which will provide a membrane thickness of up to 0.04 in. (1 mm) thick. This spraying process is accomplished using an asphalt distributor (Figure 4-22). Slopes should be 2H:1V maximum with 3H:1V preferable.

Table 4-26 lists the mix compositions which are normally acceptable for asphalt concrete used in hydraulic structures. In general an AC-20 grade asphalt cement or equivalent is used. However, the type as well as the asphalt concrete are limited by the ability of the mix to resist flowing down the slope at placement temperatures.

FIGURE 4-22

ASPHALT DISTRIBUTOR

TABLE 4-26

MIX COMPOSITIONS FOR FORMED-IN-PLACE ASPHALT LININGS

Sieve Size	A	B	C
		Percent Passing	
25.0 mm (1 in.)			100
19.0 mm (3/4 in.)		100	95-100
12.5 mm (1/2 in.)	100	95-100	--
9.5 mm (3/8 in.)	95-100	84-94	72-85
4.75 mm (No. 4)	70-84	63-79	53-72
2.36 mm (No. 8)	52-69	46-65	40-60
1.18 mm (No. 16)	38-54	34-53	30-49
600 μm (No. 30)	27-44	25-42	22-39
300 μm (No. 50)	19-33	17-32	16-30
150 μm (No. 100)	13-24	12-23	11-22
75 μm (No. 200)	8-15	8-15	8-15
Asphalt cement,[a] percent by wt. of total mix	6.5-9.5	6.5-9.0	6.0-8.5
Mix type	Well-graded (low voids)	Well-graded (low voids)	Well-graded (low voids)
Minimum recommended compacted depth	4 cm (1-1/2 in.)	5 cm (2 in.)	6 cm (2-1/2 in.)
Recommended usage	Impermeable surface	Impermeable surface	Impermeable surface

[a]AC-20, or equivalent AR- or penetration grade, recommended.

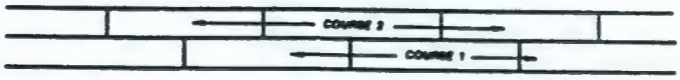
Source: Asphalt Institute (1976)

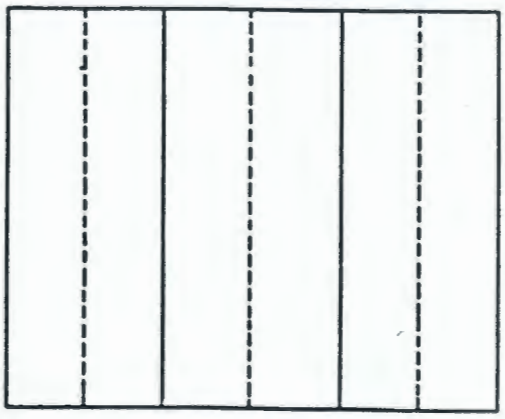
9 3 1 2 9 0 4 1 0 9 2

When the asphalt concrete barrier is placed in two or more courses (layers), as is desirable to minimize joint seepage, the joints should be offset (Figure 4-23). The exposed edge of the asphalt concrete at the joint should have an approximate slope of 1H:1V to ensure a good impermeable seal.

FIGURE 4-23

JOINTS FOR ASPHALT CONCRETE





JOINTS FOR COURSE 1

JOINTS FOR COURSE 2

4.6.3.4 Geomembranes

Polymeric membranes (also known as geomembranes) have been utilized extensively in the field of hazardous waste disposal. One of their big advantages is that they come to the site in a prefabricated form (for the most part). The sheeting itself (excluding the field seams) has not had to endure the rigors of the site climate in their manufacture. However in all but the very smallest jobs, one sheet (or panel) does not completely cover the project. Therefore, the panels must be seamed in the field. The field seam is the portion of the geomembrane barrier that is its weakest link. Failures of field seams result from a number of causes:

- Surface contamination.
- Moisture or excessive humidity.
- Too low or too high a temperature (material).
- Defective adhesive.
- Improper adhesive system employed.
- Solvent evaporates before seam is made.
- Insufficient time allowed for tack to develop.
- Improper alignment of panels.
- Insufficient dwell time (time in which pressure is applied to the seam).

The geomembrane's manufacturer should be consulted as to the proper seaming system to be used. Also, installers who have experience with a particular seaming system should be preferred over others.

Generally there are two forms in which polymeric membranes are manufactured: reinforced and unreinforced. The reinforced membrane is considered when tensile stresses (such as those generated on a steep slope) are present. The unreinforced alternative is generally considered when the polymeric material is expected to stretch to avoid failure (such as during subsidence).

The following tests provide the designer with the information needed to evaluate the polymeric material under consideration.

Properties	Test Method
Thickness, mils., ± 5%	ASTM D-1593
Tensile Strength, min., psi (lbs./in. width, min.)	ASTM D-882
Modulus @ 100% Elongation min. psi (lbs./in. width, min.)	ASTM D-882
Ultimate Elongation, % min.	ASTM D-882
Tear Resistance:	
(a) Elmendorf, grams, min. (gms./mil., min.)	ASTM D-1922
(b) Graves Tear, lbs. min. (lbs./in. min.)	ASTM D-1004
Low Temperature Impact, Pass, °F	ASTM D-1790
Volatility, % loss, max.	ASTM D-1203
Water Extraction (@ 104°F, 24 hrs.) % loss, max.	ASTM D-1239
Specific Gravity, min.	ASTM D-792
Dimensional Stability (@ 212°F, 15 min.) % max. change	ASTM D-1204
Resistance to Soil Burial:	
Tensile Strength Loss, % max.	ASTM D-3083
Peel adhesion	ASTM D-413

The manufacturers of polymerics have various modifications to these tests which are said to better reflect their products' quality. However, the standard version of the test should be considered the minimum requirement and the primary evaluation based on it.

An alternative or backup to seaming is "shingle" construction. This simply involves a large overlap between the edge of one sheet and the edge of the underlying sheet. The overlying edge should point down hill, just as in the shingling on a roof. After the membrane sheeting is covered with soil, the weight of the soil serves to hold the two sheets in contact with one another, thus affording only an extremely narrow, long flow channel for water. Such construction would probably not be acceptable in a liner, but might well be satisfactory in a cover.

The question of how steep a slope a geomembrane may be placed on is an open one and the subject of current research. One consideration is the tensile strength of the membrane itself, and another is the possibility of shipping or sliding either of the overlying soil along the membrane or of the membrane itself along its substrate. Martin, Koerner, and Whitty (1984) reported on frictional behavior between four geomembrane materials and three granular soils. Measured friction angles ranged between 17 and 27 degrees, with the commonly used HDPE consistently showing the lowest friction angles. The interested reader should consult Martin, Koerner, and Whitty's paper.

4.7 Drainage Layer

4.7.1 General Principles

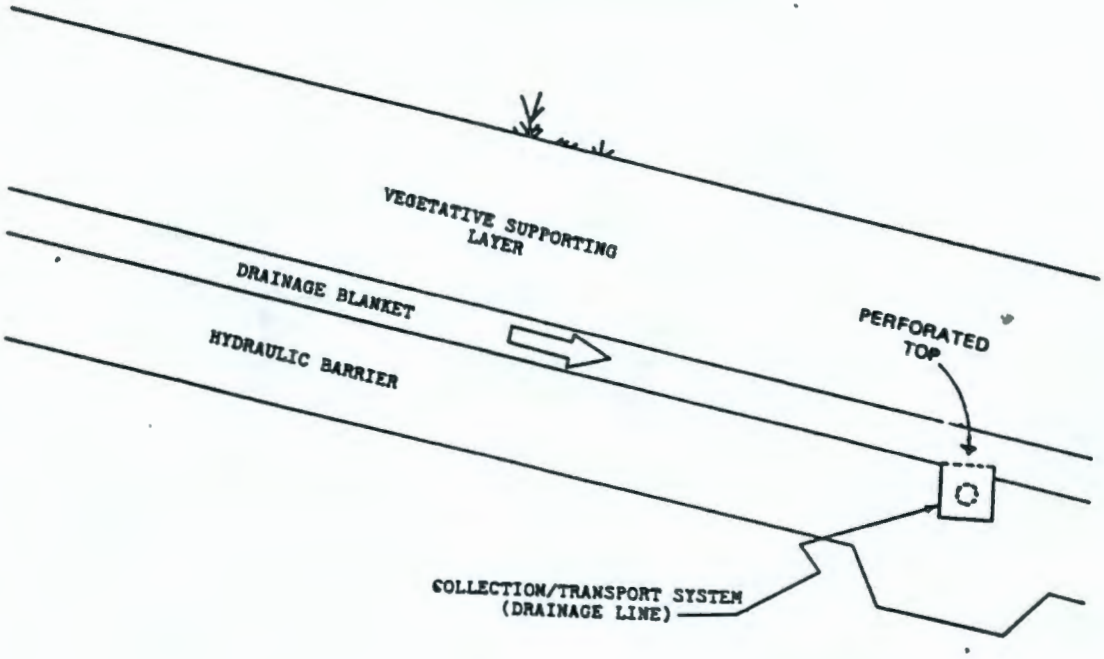
The primary functions of the drainage layer in a multilayer cover system are to intercept any water that percolates down through the layer or layers above and to transport this water to a safe disposal outlet. For most cases, it will consist of a drainage blanket and a collection/transport system (Figure 4-24). The drainage blanket may consist of a sand and gravel layer. The collection/transport system may consist of gravel drains. A complex collection/transport system might incorporate a series of collectors, laterals, and main lines (Figure 4-25) to direct and dispose of the water entering the drainage system. The complexity of the system will depend on the area to be drained, flows to be handled, and other site-specific details.

The collector (usually a gravel drain) takes the water from the drainage layer and transfers it to a lateral which in turn either transfers the water to a main (to go to an outlet) or directly to an outlet. The basic difference between a collector and a lateral or main line is that the lateral does not receive water directly from the drainage blanket.

The following variables affect the design of the drainage layer:

FIGURE 4-24

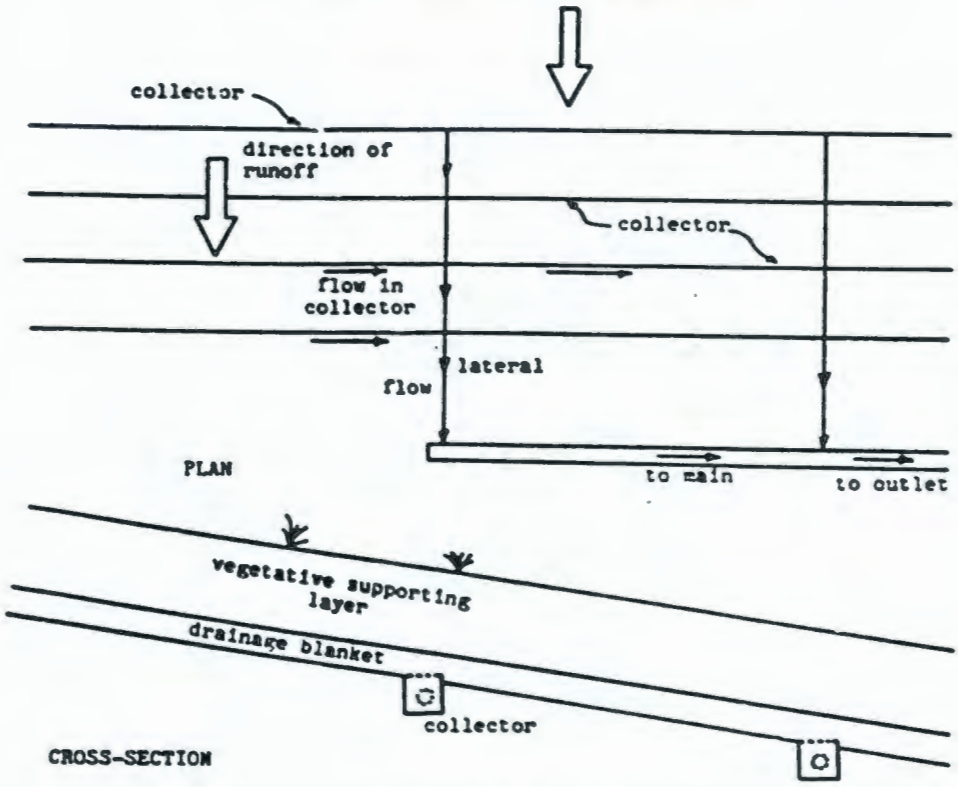
DRAINAGE LAYER SCHEMATIC



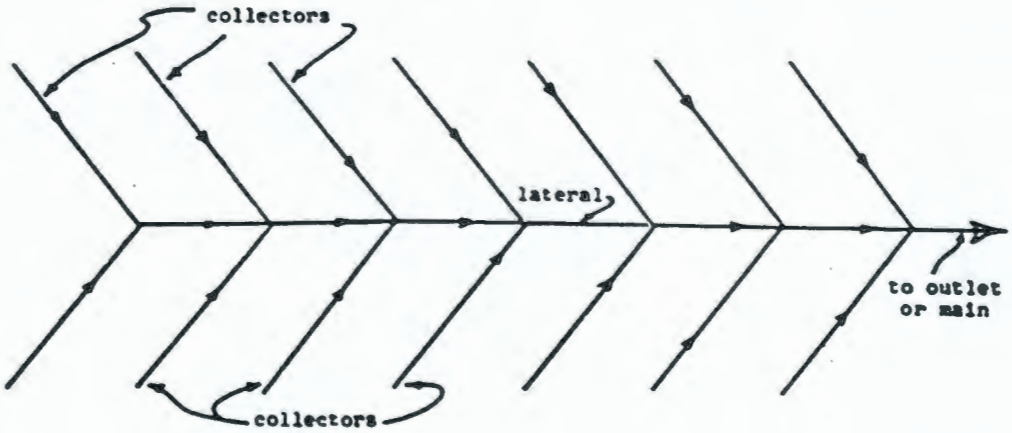
9 3 1 2 9 0 4 1 0 9 6

FIGURE 4-25

COLLECTION/TRANSPORT SYSTEM PATTERNS



a. Parallel Pattern



b. Herringbone Pattern

- Intensity of the design storm
- Evapotranspiration rate
- Rate of runoff at the surface
- Permeability of the upper layer (or layers)
- Permeability of the lower layers (hydraulic barrier in particular)

The precipitation rate normally used in designing a drainage layer is that which occurs in one hour in a ten-year storm. The amount of water that is not handled as runoff by the surface water management plan enters the vegetative layer as infiltration. Details of infiltration and runoff are discussed above in section 4.2.

The reader may also wish to consult the informative discussion of subsurface drainage for agriculture in Schwab et al. (1981).

4.7.2 Subsurface Drainage Design

The following formula is presented by Moore (1980) as a method of calculating the thickness of a sand and gravel drainage blanket (see Figure 4-26):

$$h_{max} = \frac{L\sqrt{c}}{2}\left[\frac{\tan^2\alpha}{c} + 1 - \frac{\tan\alpha}{c}\sqrt{\tan^2\alpha + c}\right]$$

where

h_{max} = height to which water will rise in the blanket layer
L = twice the distance between drains
$c = e/k_s$
α = slope angle
e = rate at which water impinges upon the drainage layer
k_s = saturated permeability of the drainage blanket

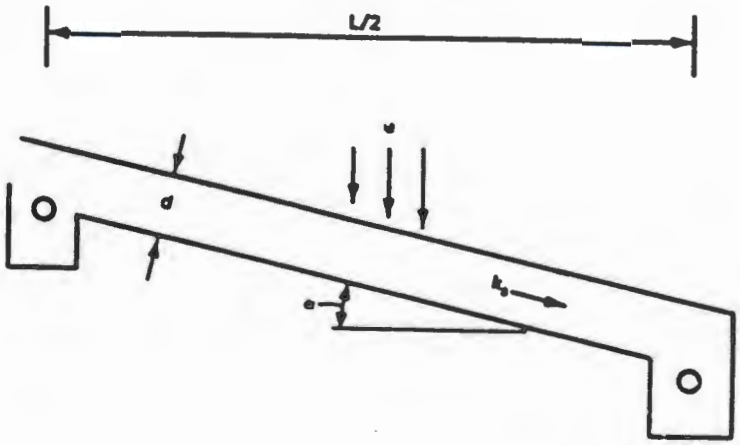
The thickness of the drainage blanket (d) should always be kept greater than h_{max}. Determining the thickness of the drainage blanket then becomes a process of adjusting α, k_s, and L to comply with the design infiltration rate. The equation assumes that all water above the upgradient drain will be captured by the upgradient drain.

If a sand-and-gravel filter is used with a drainage blanket, then a "weighted" coefficient of permeability should be used. The following formula (Departments of the Army and Air Force, 1979) gives a reasonable design value for same:

$$k = \frac{k_1d_1 + k_2d_2 + k_3d_3 + \ldots}{d_1 + d_2 + d_3 + \ldots}$$

FIGURE 4-26

DRAINAGE BLANKET ELEMENTS



where

k = weighted coefficient of permeability (for flow parallel to layering)

$k_1, k_2, k_3 \ldots$ = coefficients of permeability on individual base materials

$d_1, d_2, d_3 \ldots$ = thicknesses of the individual layers

Another method of determining collector spacing (Department of the Navy, 1982) involves determining the effective porosity "n_e" of the drainage blanket by the following formula:

$$n_e = 1 - \frac{\gamma_d}{G_s \gamma_w} (1 + G_s w_e)$$

where

γ_d = dry density of the material

G_s = specific gravity of the solids

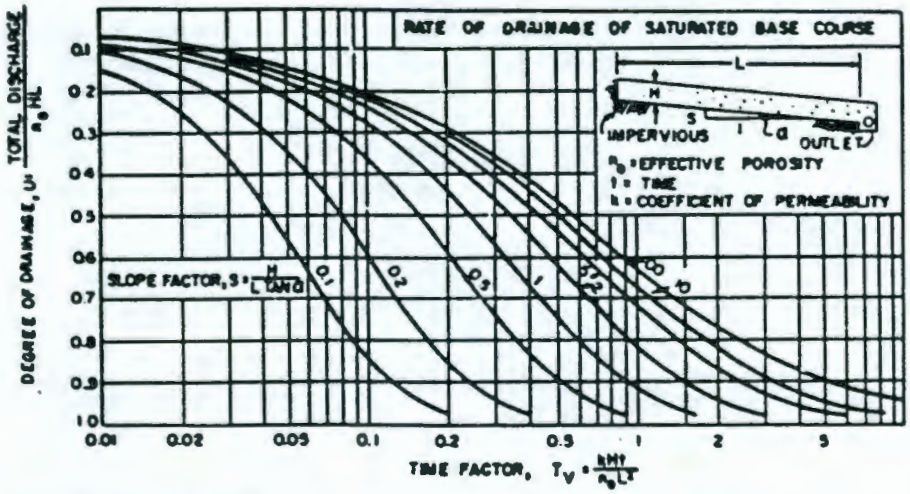
γ_w = unit weight of water

w_e = effective water content (after the specimen has drained water to a constant weight) expressed as a decimal fraction relative to dry weight)

Values for n_e usually run from 0.15 for bank-run sands to not more than 0.25 for uniformly graded medium or coarse sands. This value is then used with Figure 4-27 to determine the drainage blanket characteristics. Figure 4-28 presents some examples of coefficients of permeability for clean coarse-grained drainage material recommended for use in initial estimates.

FIGURE 4-27

ANALYSIS OF DRAINAGE LAYER PERFORMANCE



Select drain spacing, L, so that 50% drainage will be completed in 10 days.

$$t_{50} = \frac{T_v n_e L^2}{KH}$$

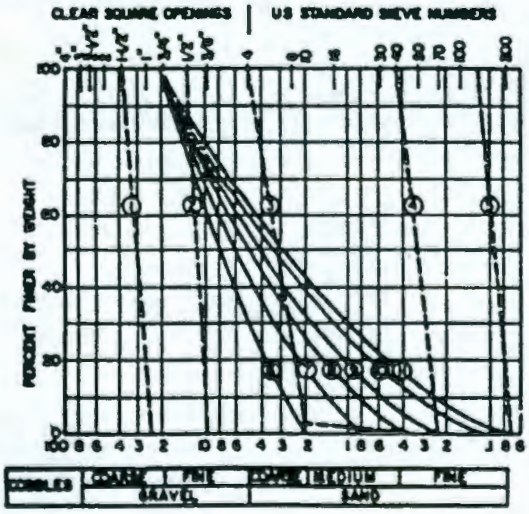
For estimate use: $t_{50} = \frac{n_e L^2}{2K(H + L \tan\alpha)}$

t_{50} drainage rate: $q = KH\frac{(H + L \tan\alpha)}{2L}$

From Department of the Navy, 1971

FIGURE 4-28

CHARACTERISTICS OF CLEAN COARSE-GRAINED DRAINAGE MATERIAL



COEFFICIENT OF PERMEABILITY FOR CLEAN COARSE-GRAINED DRAINAGE MATERIAL

CURVE	K, FT/MIN.
1	73.7
2	56.9
3	5.41
4	0.13
5	0.01
6	2.08
7	1.81
8	0.70
9	0.22
10	0.08
11	0.01

From Department of the Navy, 1982

9 3 1 2 9 0 4 1 1 0 0

4.7.3 Collectors

Once the physical and drainage characteristics of the drainage blanket have been determined, then a collector must be designed to handle that capacity. Lee et al. (1984) provide the following guidance as to the minimum capacity a collector (also applicable to laterals and mains) should have for different slopes:

Slope	Water Removal Rate (cfs/1000 ft of Pipe)
Less than 2%	1.50
2 to 5%	1.65
6 - 12%	1.80
12%	1.95

General details of gravel collectors are shown in Figure 4-29. Criteria for filter media are found in section 4.4.

One approach to collector design is to design the pipe to handle the flow using the same design procedures as for open channel flow (Manning's equation) and then meet the specifications for a minimum gravel cover of 6 in. on the top and sides and 2 in. below (Department of the Navy, 1971). The gravel used for this purpose should have a higher coefficient of permeability than the drainage blanket. However, another simplified approach involves the use of charts and nomographs. Generally the design steps are as follows:

- Determine the maximum flow and/or velocity the pipe (collector, lateral, or main) must carry.
- Determine the slope (gradient) of the drain.
- Establish the type of pipe to be used and obtain the coefficient of friction.
- Obtain a chart or nomograph for that particular value of n and enter it with the required values of flow, gradient, or velocity and determine the size of pipe required.

Figures 4-30 and 4-31 present examples of such charts and nomographs.

Table 4-27 presents some guidance as what should be specified when considering a subsurface drainage system. Details of support for drainage tubing are given in Table 4-28 and Figure 4-32. Figure 4-33 shows animal guards which should be installed in the drain outlet.

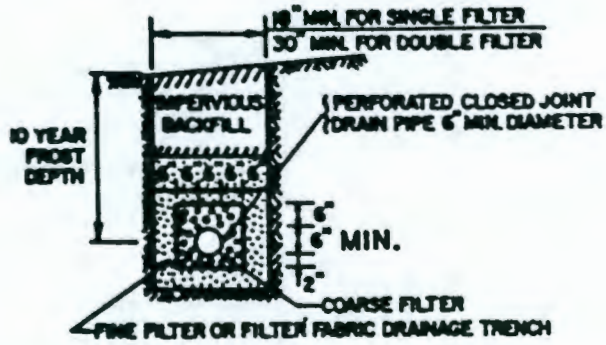
4.7.4 Agricultural Drain Tiles

Although agricultural drainage tiles of concrete and clay carry water at a

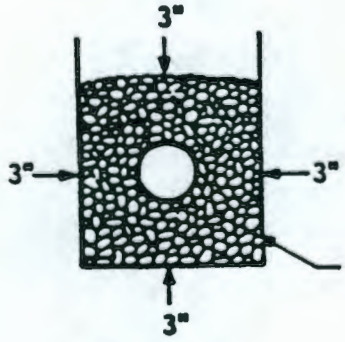
FIGURE 4-29

GRAVEL COLLECTOR CHARACTERISITCS

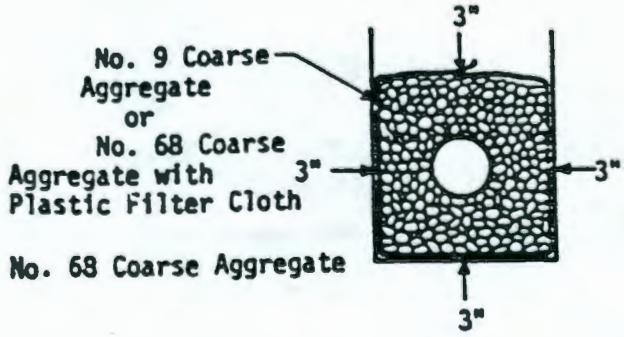
NOTE:
THE FINE FILTER SHOWN CAN BE DELETED AND REPLACED WITH FILTER FABRIC (IF SUITABLE)



Source: Department of the Navy (1982)



Envelope



Filter

Coarse Aggregate Gradations*

Grade	Percent	Sieve Size
No. 9	100	3/8 inch
	92 % 8	#4
	25 % 15	#8
	10 (Maximum)	#16
	5 (Maximum)	#50
No. 68	100	1 inch
	95 % 5	3/4 inch
	48 % 17	3/8 inch
	20 (Maximum)	#4
	6 (Maximum)	#8
	5 (Maximum)	#16

*Virginia Department of Highways and Transportation Specifications. Open Graded, Percent by Weight.

Source: Lee et al. (1984)

93129041102

FIGURE 4-30

SUBSURFACE DRAIN CAPACITY, n = 0.025 (LEE ET AL., 1984)

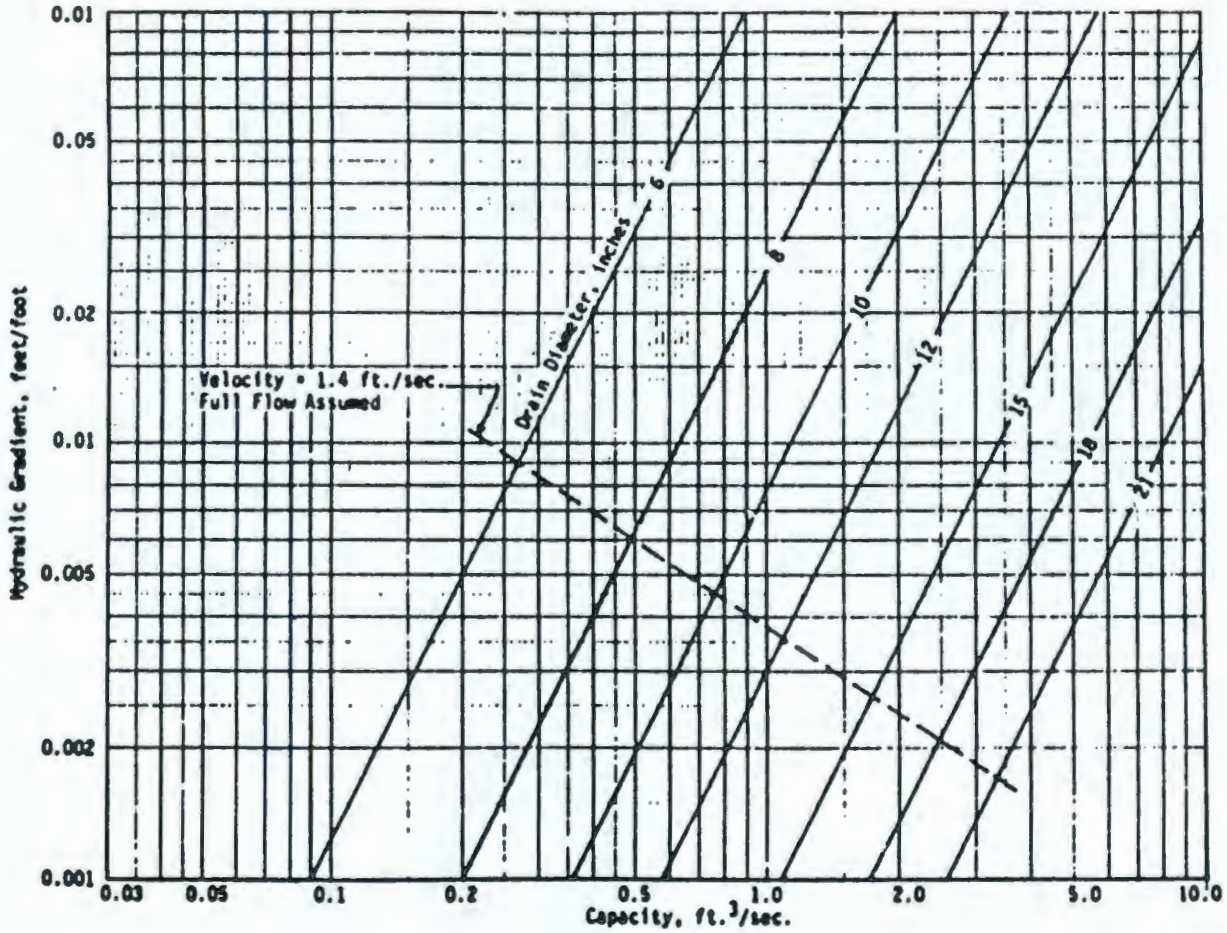


FIGURE 4-31

AIRFIELD DRAINAGE NOMOGRAPH FOR COMPUTING REQUIRED SIZE OF CIRCULAR DRAIN, FLOWING FULL, n = 0.013 AND n = 0.024 (DEPARTMENTS OF THE ARMY AND AIR FORCE, 1979)

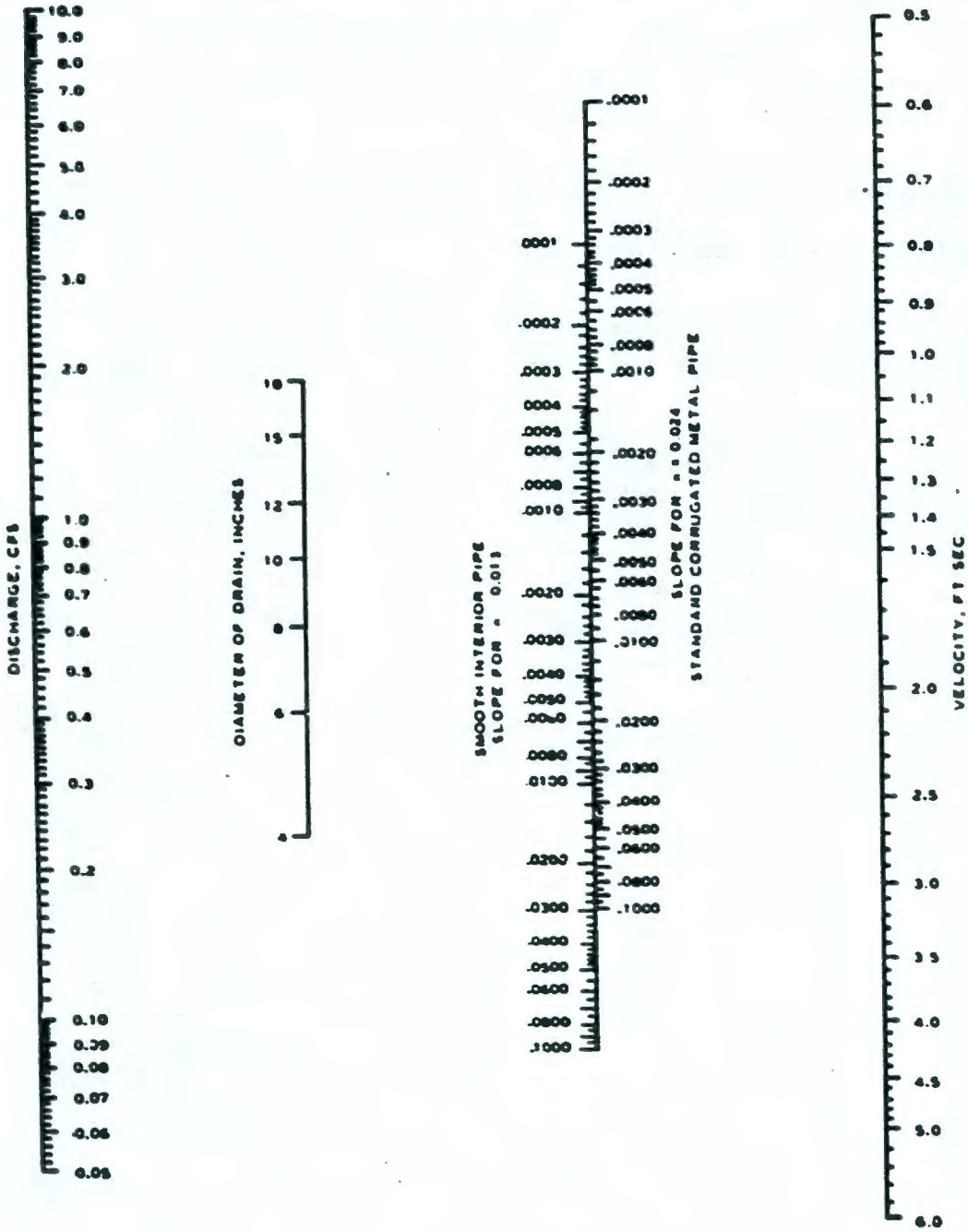


TABLE 4-27

GUIDANCE FOR SUBSURFACE DRAINAGE SYSTEMS

a. Rejected tiles should be broken so they will not be used inadvertently elsewhere.

b. Clay and concrete tile should not be stockpiled in contact with the ground.

c. A minimum clearance of 50 ft should be maintained between drain lines and any trees and shrubs. For water-loving trees such as willow, elm, cottonwood and soft maple, this distance should be increased to 100 ft.

d. Soft or yielding soils which will serve as a foundation for the drainage lines should be stabilized to protect the lines from settlement which could alter drainage gradients.

e. All subsurface drains should be laid to line and grade and covered according to one of the methods outlined in Figure 4-43. If anticipated future subsidence is predictable and small, grade may be adjusted to allow for same.

f. Backfill should be placed in a manner that will not cause displacement of the drain.

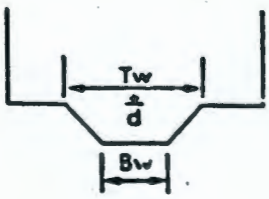
g. Laterals and mains should be bedded in a proper trapezoidal or circular groove (Table 4-28).

h. The outlet should be protected against surface flow and an animal guard installed (Figure 4-33).

TABLE 4-28

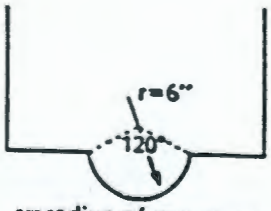
ALLOWABLE TRAPEZOIDAL* GROOVES FOR BEDDING CORRUGATED POLYETHYLENE DRAINAGE TUBING

Nominal Tube Diameter (d) (Inches)	Groove (d) depth (Inches)	Groove (Tw) top width (Inches)	Groove (Bw) bottom width (Inches)
4	1.1	4.1	1.8
5	1.4	5.1	2.3
6	1.7	6.2	2.9
8	2.1	8.0	3.7
4 & 5	1.5	5.1	2.1
4, 5, & 6	2.0	6.2	2.3
4, 5, 6, & 8	2.8	8.0	2.4**
6 & 8	2.4	8.0	3.3
5, 6, & 8	2.5	8.0	3.0



*These trapezoidal grooves with 45-degree side slopes will provide support similar to that provided with a circular groove shaped to fit the lower 120° of circumference.

**The groove dimensions shown on this line are for use with the semi-trapezoidal groove shown below. Bottom radius of curvature must be 6 inches or less.

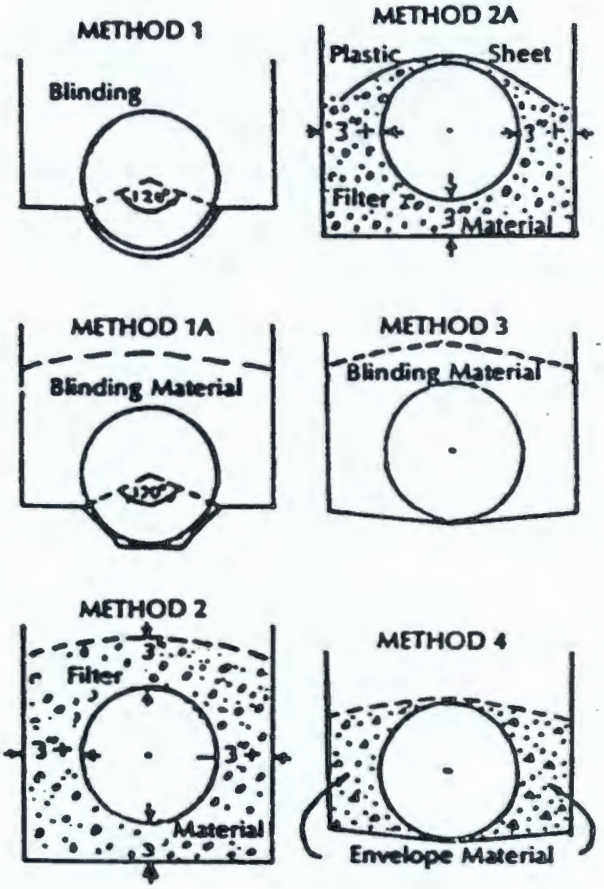


r=radius of curvature

(Georgia, n.d.; cited in Lee et al., 1984)

FIGURE 4-32

METHODS OF PLACING SUBSURFACE DRAINS

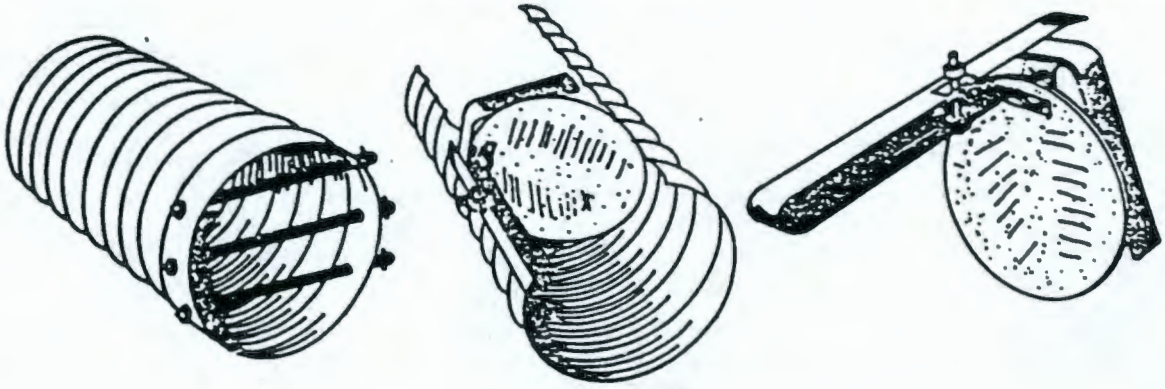


Type of Conduit	Special Conditions	Method
1. Flexible	Filter not required	1 or 4
2. Flexible	Filter required	
	a. Prefabricated	1
	b. Sand and gravel filter	2
3. Rigid	Filter not required	1 or 3
4. Rigid	Filter required	
	a. Prefabricated filter	1 or 3
	b. Sand and gravel filter	4
5. Flexible or rigid	Envelope required	4

(Georgia, n.d.; cited in Lee et al., 1984)

FIGURE 4-33

SMALL-ANIMAL GUARDS



(Georgia, n.d.; cited in Lee et al., 1984)

much slower rate than drains using pipes, their usefulness should not be overlooked. At sites where a small amount of precipitation falls or where a potentially damaging seep emerges and needs to be diverted, the drain tile may be more than adequate and more cost-effective. Specifications for drain tiles are presented in Table 4-29. A source of guidance for agricultural drainage practices is Van Schilfgaarde (1974). Design factors in agricultural subsurface drainage are also discussed in Bouwer (1978).

4.7.5 Exit Design

A problem that is often overlooked and just as often causes problems is the velocity and volume of the water in a drainage blanket at its lowest point (its end). This water may exit at too high a velocity if not intercepted prior to exiting, and carry soil particles with it or cause a destabilization of the slope at the toe of the drainage blanket. An example of this problem may be found in the discussion of the Sylvester hazardous-waste site in Appendix B, "Case Histories." Two methods of intercepting this water are the toe drain (Figure 4-34) or installing a graded riprap filter. Also refer to Appendix H, "Outlet Structures."

4.8 Biotic Barrier

Figure 4-1 shows a biotic barrier layer above the drainage layer and beneath the surface layer. The need for such a layer arises from the threat of damage to the hydraulic barrier by intrusion of plant roots and burrowing animals (sec. 4.6.2.3.).

9 3 1 2 9 0 4 1 1 0 8

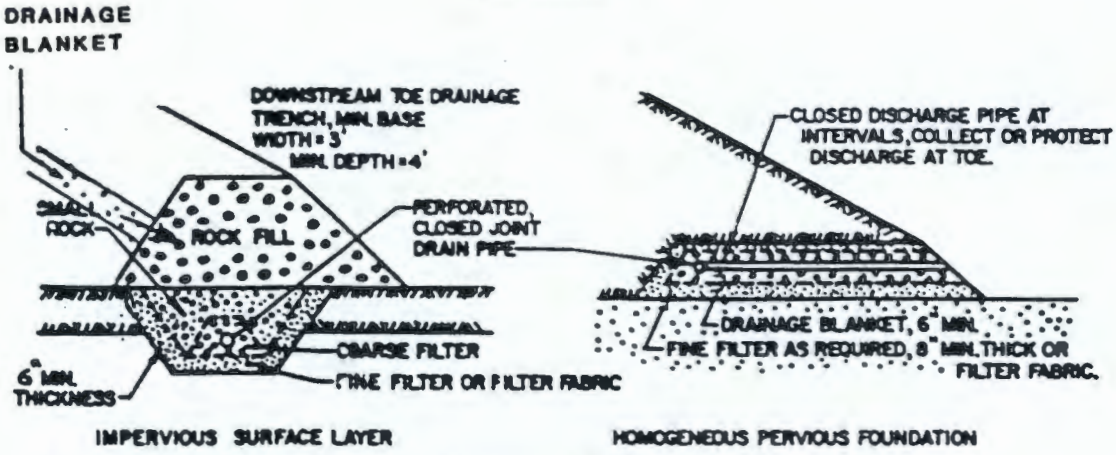
TABLE 4-29

GUIDANCE FOR TILE SPECIFICATIONS

1. Connections, depth limitations, blinding, backfilling, and protection of the line during installation should be in accordance with local specifications.
2. Joints: Crack width for lateral tile should vary with the type of soil:
   a. Peat and muck - 1/4 inch preferred; 3/8 inch maximum
   b. Clay soils - 1/8 inch preferred; 1/4 inch maximum
   c. Silt and loam soils - 1/16 inch preferred; 1/8 inch maximum
   d. Sandy soils - tightest fit possible.
3. When the tiles are laid in fine sand, they should be turned as necessary to leave the least possible crack opening and a filter should be provided to prevent the fine material from entering the tile.
4. Crack opening for mains which serve only to collect and transport drainage water from lateral tile lines should be the tightest fit possible.
5. Alignment. A change in horizontal direction may be made by using one of the following methods:
   a. A gradual curve of the tile trench on a radius that the trenching machine can dig and still maintain grade. Tile must be shaped or chipped so that no crack between tiles exceeds 1/8 inch unless the crack is adequately covered to exclude soil movement to the tile.
   b. A manufactured or handmade bend or fitting for small diameter tile.
   c. A junction box or manhole for large diameter tile.

FIGURE 4-34

TOE DRAIN



Adapted from Department of the Navy, 1971

As far as is known, such a layer has never been emplaced at an actual hazardous-waste-site cover installation. It is therefore impossible to give a proven working design. It is only possible to report some research results.

Research at Los Alamos National Laboratory and elsewhere has yielded a rule of thumb for stopping burrowing animals. If objects in the animal's path are too large for him physically to move and tightly enough packed, his progress is effectively stopped. Thus a biobarrier can consist of cobblestones, brick rubble, or any solid pieces of inert material, as long as large air pore spaces are present between pieces. This type of material also creates an environment that plant roots cannot survive.

Parry, Bell, and Jones (1982) described a chemobarrier cover system designed for an abandoned copper-smelter waste pile in England. An 18-in. cover layer of an alkaline sodium carbonate waste (pH 9-12) was placed over the metal-mining waste, followed by 6 in. of topsoil. A golf course was then developed on the site. The alkaline waste was used to inhibit plant-root growth as well as to restrict mobility of metals from the smelter waste to the topsoil surface.

It has also been reported that root growth can be restricted by the placement of a layer of material such as cobblestones (Cline, 1979), ground limestone or pulverized fuel ash (Jones et al., 1982), or with root toxin such as ureabor (Cline, 1979).

In theory it is possible to design a "chemobarrier," that is, a layer of high or low pH that is inhospitable to plant root penetration. Examples of chemobarriers are limestone (pH 8.5) and flyash (high alkalinity), or compacted acid subsoil (pH 4.5). Combinations of acid-tolerant vegetation and an alkaline chemobarrier of flyash has potential in restricting root penetration into the waste. Likewise calcareous-soil-loving vegetation combined with a chemobarrier of a compacted extremely acid subsoil material has potential inhibiting root growth into the waste.

These concepts are theoretically sound, but largely unproven. The effect of leaching the chemobarrier into the drainage system and out of the cover system must be evaluated. The most realistic present approach is careful selection of short-rooted vegetation coupled with diligence in maintaining its health. This points up the importance of care in designing the vegetative stabilization program, discussed in the next section.

4.9 Surface (Vegetative) Layer

The surface layer is the one seen by the eye and exposed to the elements, which include rainfall and snow. This layer is subject to erosion, and other layers cannot be eroded until this one has been at least locally breached.

In this Handbook the surface layer is called the vegetative layer, because vegetation provides the primary means for controlling erosion, while at the same time promoting site aesthetics. In any humid climate, the surface will

9 3 1 2 9 0 4 1 1 1 0

inevitably become vegetated spontaneously, in all but rare circumstances (e.g., at some mine dumps). Thus, it is not a question of whether or not to vegetate, but rather one of having controlled and desirable vegetation, as opposed to having an uncontrolled and possibly detrimental vegetative community develop.

An informative discussion of vegetation at landfill covers is presented by Lutton, Regan, and Jones (1979). Several basic facts are pointed out by these authors. For one, sound and vigorous vegetation at landfill sites is usually highly cost-effective. At the same time, landfill sites pose several distinct problems regarding vegetation. Fertile soils are rarely available at landfill sites, and it is necessary to work with the inferior soils that may be present. An even more difficult problem is that a cover section designed to impede percolation presents an environment that in many ways is the direct opposite of one favorable to vegetation. Because vertical drainage is absent, roots are subject to swamping. Anaerobic conditions, detrimental to healthy roots, may develop. Conversely, cover systems designed to drain and dry quickly deprive vegetation of needed reservoirs of moisture. A drought, even a short one, may kill or severely injure the vegetative community.

For the reasons discussed above, the establishment and maintenance of a stable vegetative cover are very challenging problems. To meet them will probably require a careful and possibly a sophisticated design. Such a design is not cheap. Superfund guidance (see Chapter 1) demands that cost-effectiveness be emphasized. Regarding stable vegetation a careful design study is required, because cost-effectiveness in the long term will almost surely be different from a minimal first cost.

The purpose of this section is to discuss general and specific considerations regarding the use of plant materials adapted to the region in which the waste site is located. Much of the information herein has been drawn from an instruction report that compiled existing vegetative data for restoration of problem soil materials at Corps of Engineers construction sites (Lee et al., 1984). Guidance has also been drawn from an EPA manual for evaluating landfill cover designs (Lutton, 1982).

4.9.1 Desirable Functions of Vegetation

Vegetation shields the soil surface from the full force of impacting raindrops, reinforces the soil against the hydraulic and abrasive action of moving surface water and wind, binds the soil particles together to form a mass that is less easily displaced, and anchors the soil in place. Plant leaves, stems, and other aboveground portions of vegetation, as well as the organic litter that collects on ground surface, can also shield the soil surface. Only well-established vegetation, however, can perform all of the above functions.

The vegetative layer should perform the following functions:

- Stabilize the soil against erosion by water and wind.
- Minimize percolation down to the waste.
- Maximize evapotranspiration of moisture from the soil material cover.
- Enhance the natural beauty (aesthetics) of the site and if possible develop basic recreational and related resources at the site.
- Create self-sustaining ecosystems of low maintenance.

The first function is of major concern. The other functions should be considered to the extent possible. All of these functions must be closely linked to the long-term land-management objectives established for the specific waste site.

4.9.2 Soil Considerations

Certain factors must be considered for any soil material to be used in the vegetative layer of a cover system. The major factors determining effectiveness of a soil for supporting vegetation are grain size, pH, and organic-matter and nutrient content. A host of other factors play necessary though less critical roles. For a discussion of the influence of soil on vegetation the reader is referred to Brady (1974).

Fertile topsoil, if available for waste site cover, is usually cost-prohibitive (Lutton, Regan, and Jones, 1979). Consequently less fertile, nonproductive soils or subsoils often have to be used. Other cover materials such as dredged material may be available. A 3-ft cover of silty dredged material was used successfully to vegetate and reclaim an acid surface-mine land in Illinois (Spaine, Llopis and Perrier, 1978). Dredged material has been used to improve the productivity of marginal, low-fertility soils (Gupta et al., 1978), as well as in solid waste management (Bartos, 1977). Design consideration for waste cover systems should be given to whatever soil materials are locally available. In addition, waste materials such as sewage sludge, manure, or fly ash as a liming agent should be considered to improve the fertility of the available soil materials.

Appropriate tests can be conducted on the soils proposed for use in the vegetative layer either at a State soil testing laboratory or at commercial soil test laboratories. An advantage in using State soil testing laboratories is that their tests have been calibrated for local soil conditions with extensive field testing to back up recommendations.

Soil tests are available that can indicate if the soil material is acid, saline and sodic, excessively drained, poorly drained, or wind erodible or contains dispersive clay (Lee et al., 1984). Lutton (1982) recommends that the soil be examined according to the following sequence of factors, soil tests being performed as necessary.

9 3 1 2 9 0 4 1 1 1 2

4.9.2.1 Grain Size

Soil composed of a mixture of clay, silt, and sand such that none of the components dominates is called a loam. The stickiness of the clay and the floury nature of the silt are balanced by the nonsticky and mealy or gritty characteristics contributed by the sand. A loam is rated overall best for supporting vegetation as it is easily kept in good physical condition and is conducive to good seed germination and easy penetration by roots.

Clay-rich soils may be productive when in good physical condition, but they require special management methods to prevent puddling or breaking down or cracking of the clay granules. Silt-rich soils lack the cohesive properties of clay and the grittiness of sand, are water retentive, and usually are easily kept in good condition. Soils made up largely of sand can be productive if sufficient organic matter is present internally or as a surface mulch to hold nutrients and moisture; sandy soils tend to dry out very rapidly and lose nutrients by leaching.

4.9.2.2 Soil pH

Tests should be made to determine pH and buffering capacity (usually stated as tons/acre of calcium carbonate ground limestone necessary to adjust the soil pH to around 6.5). The amount of lime necessary to neutralize a given soil depends upon soil pore-water pH and "reserve acidity." The reserve acidity is a single factor which incorporates several variables; soils with high levels of organic matter and/or clay require higher amounts of lime for pH adjustment. The pH of subsoil (where appreciable in the cover) also influences lime requirements; acidic subsoils require higher levels and repetitive applications of lime. Some buried wastes act much like acid subsoils, making higher lime-application levels or more frequent liming intervals necessary for adequate pH control.

4.9.2.3 Organic Matter and Nutrients

Soil organic matter represents an accumulation of partially decayed and partially synthesized plant and animal residues (Brady, 1974). Such material is continually being broken down as a result of the work of soil microorganisms. Consequently, it is a rather transitory soil constituent and must be renewed constantly by the addition of plant residues.

The organic matter content of a soil is small--only about 3 to 5 percent by weight in a representative mineral topsoil. Its influence on soil properties and consequently on plant growth, however, is far greater than the low percentage would indicate. Organic matter functions as a "granulator" of the mineral particles, being largely responsible for the loose, easily managed condition of productive soils. Also, it is a major soil source of two important mineral elements, phosphorus and sulfur, and essentially the sole source

of nitrogen. Through its effect on the physical condition of soils, organic matter also increases the amounts of water a soil can hold and the proportion of this water available for plant growth. Finally, organic matter is the main source of energy for soil microorganisms. Without it, biochemical activity would come practically to a standstill.

Soil organic matter consists of two general groups: (a) original tissue and its partially decomposed equivalents, and (b) the humus. The original tissue includes the undecomposed roots and the tops of higher plants. These materials are subject to vigorous attack by soil organisms, both plant and animal, which use them as sources of energy and tissue-building material.

The gelatinous, more resistant products of this decomposition, both those synthesized by the microorganisms and those modified from the original plant tissue, are collectively known as humus. This material, usually black or brown in color, is colloidal in nature. Its capacity to hold water and nutrient ions greatly exceeds that of clay, its inorganic counterpart. Small amounts of humus thus augment remarkably the soil's capacity to promote plant production.

Soil nutrients refer to chemical elements required by plants for their growth processes. Of the fourteen essential elements obtained from the soil by plants, six are used in relatively large quantities and are thus referred to as macronutrients (Brady, 1974). They are nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Plant growth may be retarded because these elements are actually lacking in the soil, because they become available too slowly, or because they are not adequately balanced by other nutrients. Sometimes all three limitations are operative.

Nitrogen, phosphorus, and potassium are commonly supplied to the soil as farm manure and as commercial fertilizers. They are called primary or fertilizer elements. In the same way, calcium, magnesium and sulfur are referred to as secondary elements. Calcium and magnesium are added to acid soils in limestone and are called lime elements. Sulfur, other than that present in rain water, usually goes into the soil as an ingredient of such fertilizers as farm manure, superphosphate, and sulfate of ammonia, or is applied alone as flowers of sulfur.

Other nutrient elements (iron, manganese, copper, zinc, boron, molybdenum, chlorine, and cobalt) are used by higher plants in very small amounts, thereby justifying the name micronutrients or trace elements. Such a designation does not mean that they are less essential than the macronutrients but merely that they are needed in small quantities.

Table 4-30 indicates the range of concentrations of organic matter and the three primary nutrients likely to be found in soils. Results of soil tests and reference to this table will indicate that a given soil rates low, medium, etc., with regard to the substance tested for. As indicated in the table, low levels indicate the need for supplemental fertilization. Local agricultural county agents should be contacted to discuss soil fertilization requirements in relation to local climatic conditions.

9 3 1 2 9 0 4 1 1 1 4

TABLE 4-30

RELATIVE LEVELS OF ORGANIC MATTER AND MAJOR NUTRIENTS IN SOILS
(Bennett and Donahue, 1975; cited in Lutton, 1982)

Relative Level[a]	Organic Matter, percent: Sand, Loamy Sand	Sandy Loam, Loam, Silt Loam	Clay Loam, Sandy Clay, Clay	Nitrogen lb/acre	Phosphorus lb/acre	Potassium lb/acre
Very low	<0.6	<1.6	<2.6	<20	<6	<60
Low	0.6-1.5	1.6-3.0	2.6-4.5	20-50	6-10	60-90
Medium	1.6-2.5	3.1-4.5	4.6-6.5	50-85	11-20	91-220
High	2.6-3.5	4.6-5.5	6.6-7.5	85-125	21-30	221-260
Very high	>3.5	>5.5	>7.5	>125	>30	>260

[a]Medium level is typical of agricultural loam soil. Low levels need supplemental fertilization; high levels need no fertilization under normal circumstances.

Nitrogen is of special importance in establishing vegetation, because it is needed in relatively large amounts for vigorous growth but is easily leached from the soil. Nitrogen fertilizer requirements depend upon the amount of organic matter present, except for peat soil, and the release of nitrogen from the organic matter (higher organic-matter levels requiring lower application rates), the soil texture (more is required on sandy soils), and the seed mixture chosen (more is required for grasses than legumes). For average soils 50 to 85 lb/acre of nitrogen is recommended. Fertilizers are rated by the amount of nitrogen they contain per weight of fertilizer (e.g., 6 percent nitrogen). To calculate the amount of fertilizer necessary to furnish the recommended amount of nitrogen, simply divide the recommended application by the fractional amount of nitrogen the fertilizer to be used contains. For example, to apply 50 lb/acre nitrogen using fertilizer containing 6 percent nitrogen, divide 50 by 0.06 to get 833 lb/acre fertilizer required. Table 4-30 indicates a rough range of nitrogen levels present in a typical loam with moderate levels of organic matter.

Customary levels of phosphorus in soil are shown in Table 4-30. Unlike nitrogen, phosphorus is less mobile in the soil and thus is lost very slowly by leaching. It is possible to give enough phosphorus in one application to last several growing seasons. Generally at least 15 lb/acre of phosphorus* is recommended as a starter. The availability of phosphorus to the plant is quite dependent on pH. At optimum pH values (6.2-6.8) amounts of 50 lb/acre

[a]In calculating on the basis of P^2O^5, percent P^2O^5 is 2.3 times an equivalent percent phosphorus; thus 34 lb. of P_2O_5 is required to yield 15 lb. of elemental P .

are usually adequate; at pH values below 6.2 or between 6.9 and 7.5, about 80 lb/acre is needed for optimum growth. Under very alkaline conditions (pH greater than 7.5), phosphorus levels of 110 lb/acre are required. These recommendations are for freshly excavated subsoils, or for sandy or high clay soils of low organic material content. See Brady (1974) for a detailed discussion of relations between pH and soil phosphorus. Phosphorus is extremely important for legume establishment.

Potassium is much less important in grass establishment than in legume establishment and maintenance; thus the rate of application depends upon both soil test results and species to be seeded. A minimum application of 26 lb/acre potassium (32 lb/acre K_2O) as a starter is recommended under any circumstances. Applications can run as high as 230 lb/acre potassium (277 lb/acre K_2O) on impoverished soils where legumes are to be seeded. Potassium is moderately mobile in the soil and is slowly leached out, but one heavy application should be adequate for several growing seasons.

4.9.2.4 Thickness of Soil Layer

The thickness of the surface vegetative-support layer is a matter of some uncertainty. Economics is an obvious inducement for the minimum tolerable thickness, as there will be less material and placement cost. However, the thicker the layer the more stable it will be, and also the more likely to be able to support desirable naturally deep-rooted plants such as legumes (discussed below). The Resource Conservation and Recovery Act (RCRA) specifies a minimum surface-layer thickness of 2 ft for controlled landfill covers, and this would seem to be a desirable minimum at uncontrolled sites as well.

Among the factors to be considered is the need to retain enough moisture in the surface layer to sustain vegetation through dry periods. This question was studied by Miller and Bunger (1963), who measured soil drainage behavior in a sandy-loam soil layer of 2 ft minimum thickness underlain by more granular soils. Their work showed that the sandy loam retained moisture better if it was underlain by a free-draining layer than if it was continuous downward. A "wick" effect seemed to be operative, suggestive that interruption of capillary-type downward flow by the more granular layer served to "trap" the moisture in the sandy-loam layer.

4.9.3 Appropriate Vegetation

Each species of grass, legume, shrub, or tree has its own environmental and biological strengths and limitations. Moisture, light, temperature, elevation, aspect, balance and level of nutrients, and competitive cohabitants are all parameters which favor or restrict plant species. The selection of the best plant species for a particular site depends upon knowledge of adapted plants that have the desired characteristics (Lutton, 1982).

Guidance in the selection of appropriate plants for establishing vegetation on cover systems at waste sites is provided below. Most of the detailed information has been obtained from Lee et al. (1984). Supplemental information can be obtained from the sources given in Chapter 2.

Plant growth regions are delineated in Figure 4-35 for the arid and semiarid climates of the Western United States and in Figure 4-36 for the subhumid and humid climates east of approximately the 100th meridian. Plant species will be discussed and designated according to these plant growth regions. Tables 4-31 and 4-32 list plant species that clearly have value and/or promise for use on various waste cover systems in arid, semiarid, subhumid, and humid climates of the conterminous United States (Graham, 1941; Hafenrichter et al., 1979; Clements, 1920; Martin et al., 1951; U. S. Department of Agriculture, 1937; Mueller-Dombois and Ellenberg, 1974). Additional information for each species is contained in Lee et al. (1984).

Several considerations that are highly relevant in developing the vegetative layer of waste cover systems are:

- Criteria for selecting grasses and forbs
- Criteria for shrubs and trees
- Breeding and selecting plants for tolerance to stress
- Source of seeds
- Use of single species versus species in mixture
- Use of adapted native versus introduced plants
- Undesirable species

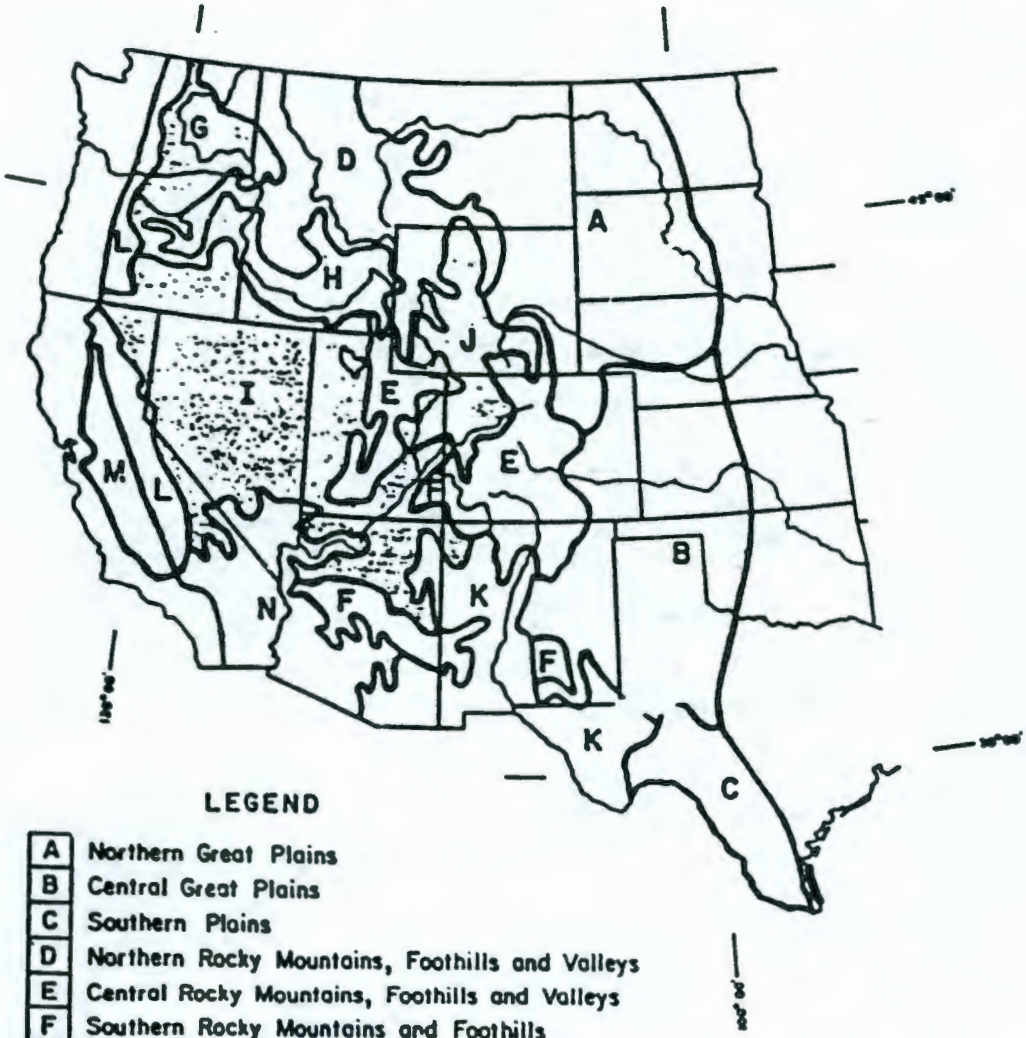
4.9.3.1 Criteria for Selecting Grasses and Forbs

The following criteria should be considered in selecting grasses and forbs (herbaceous nonlegumes and legumes) for the control of soil erosion and surface runoff (adapted from U. S. Environmental Protection Agency, 1976):

- Availability in required quantity and in the appropriate season
- Rapid germination and development
- Ability to withstand the erosive and traffic stresses present at the site being covered
- Adaptability to cover soil conditions (pH, texture, drainage, salinity, sodicity, and wind erosion)

FIGURE 4-35

PLANT GROWTH REGIONS OF THE ARID AND SEMIARID AREAS OF THE WESTERN UNITED STATES (THORNBURG, 1979)



LEGEND

A	Northern Great Plains
B	Central Great Plains
C	Southern Plains
D	Northern Rocky Mountains, Foothills and Valleys
E	Central Rocky Mountains, Foothills and Valleys
F	Southern Rocky Mountains and Foothills
G	Palouse Prairie, Columbia Basin and Plateau
H	Snake River Plain and Eastern Idaho
I	Great Basin Intermontane
J	Northern and Central Intermountain Desertic
K	Southern Plateaus
L	Cascade - Sierra Nevada
M	California Valley and Foothills
N	Southwestern Desert

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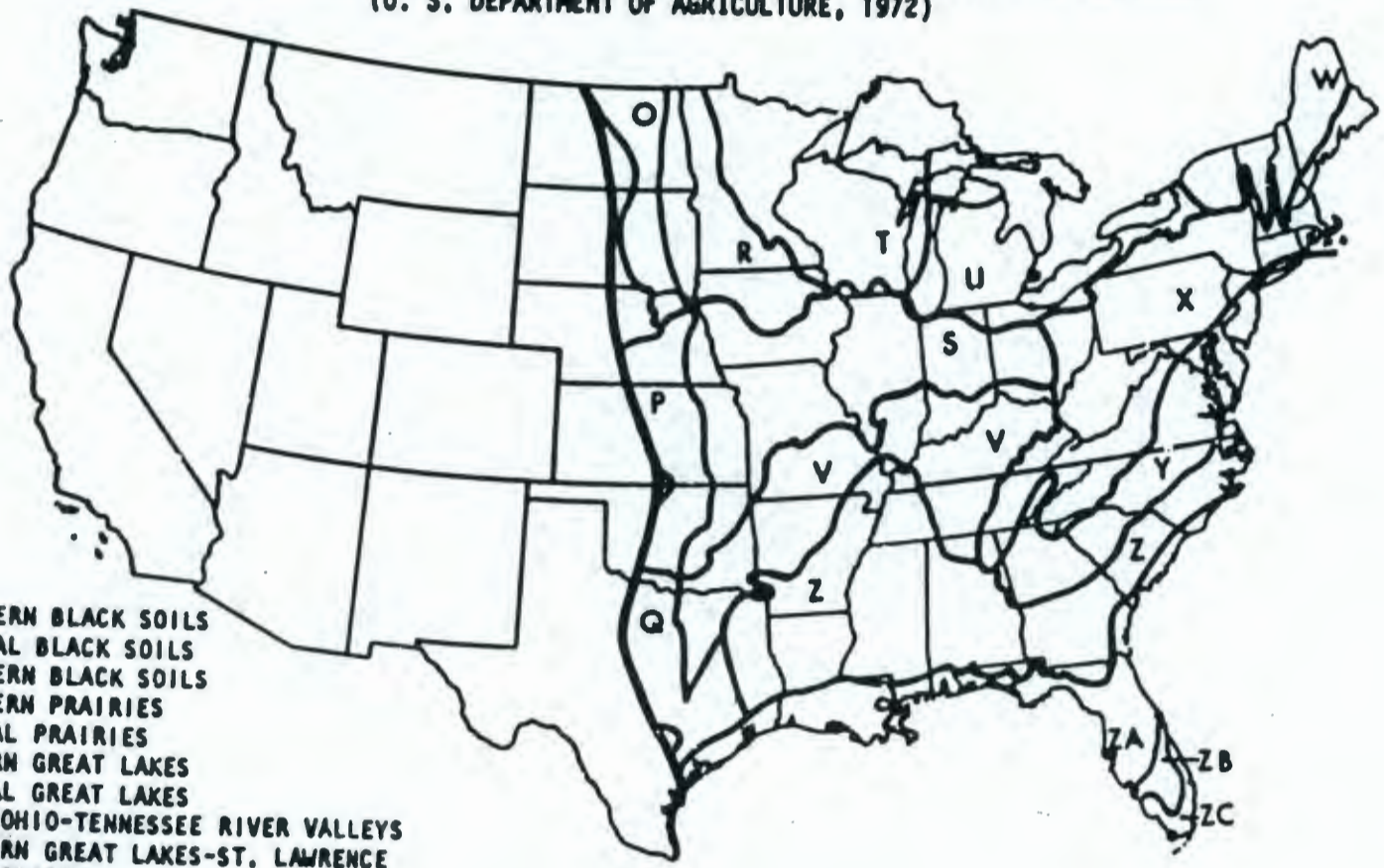
FIGURE 4-36

PLANT GROWTH REGIONS OF THE UNITED STATES FOR THE HUMID AND SUBHUMID CLIMATES
(U. S. DEPARTMENT OF AGRICULTURE, 1972)



O NORTHERN BLACK SOILS
P CENTRAL BLACK SOILS
Q SOUTHERN BLACK SOILS
R NORTHERN PRAIRIES
S CENTRAL PRAIRIES
T WESTERN GREAT LAKES
U CENTRAL GREAT LAKES
V OZARK-OHIO-TENNESSEE RIVER VALLEYS
W NORTHERN GREAT LAKES-ST. LAWRENCE
X APPALACHIAN
Y PIEDMONT
Z UPPER COASTAL PLAIN
ZA SWAMPY COASTAL PLAIN
ZB SOUTH-CENTRAL FLORIDA
ZC SUBTROPICAL FLORIDA

TABLE 4-31

CHARACTERISTICS AND SUITABILITY OF LEGUMES RECOMMENDED FOR VEGETATIVE SURFACE COVER

Name		Soil in Humid Climate			Soil in Arid and Semiarid			Wind Erosion Control	Season		Longevity		Lower pH Tolerance	Optimum Annual Precipitation Zone	Recommended Plant Growth Regions*	
Common	Scientific	Acid	Excessively Drained	Poorly Drained	Saline-Alkaline	Excessively Drained	Poorly Drained		Warm	Cool	Annual	Perennial			Humid Climate	Arid and Semiarid
Lespedeza, serices	*Lespedeza cuneata*	X	X						X			X	4.5		P,Q,S,V,X,Y,Z	
Lespedeza prostrate	*Lespedeza cuneata* "Ky 530"	X	X						X			X	4.5		P,Q,S,V,X,Y,Z	
Trefoil, birdsfoot	*Lotus corniculatus* var. "v.king"	X								X		X	4.5		O,P,R,S,T,U,W,X,Y, & N. Pacific coast	
Trefoil, birdsfoot	*Lotus corniculatus*		X	X			X			X		X	5.0 to 7.5	18-20+	O,P,R,S,T,U,W,X,Y, & N. Pacific coast	A,B,D,E,F,G,H, I,X
Flatpea, "Lathco"	*Lathyrus sylvestris* var. "Lathco"	X	X							X		X	4.5		O,P,Q,R,S,T,U,V,W, X,Y,Z	
Lespedeza, common	*Lespedeza striata* var. "Lobe"	X							X		X		4.5		S,V,X,Y,Z,ZA,ZB	
Lespedeza, Korean	*Lespedeza stipulacea*	X							X		X		5.0		S,V,X,Y,Z	
Crotalaria	*Crotalaria lanceolata*	X							X		X		4.5		V,X,Y,Z,ZA,ZB	
Vetch, crown	*Coronilla varia*		X							X		X	5.0 to 7.5		O,P,R,S,TU,W,X,Y, & N. Pacific coast	
Vetch, hairy	*Vicia villosa*				X	X				X	X			18-20+		A,B,E,G,H,I
Alfalfa	*Medicago sativa*					X	X			X		X		17-20+		A,B,D,E,F,G,H, I,J,K,L,M,N
Sweet clover, white	*Melilotus alba*		X			X	X			X	X		6.0 to 8.0	16-20+	O,P,Q,R,S,T,U,V,W, X,Y,Z	A,B,D,E,F,G,H, I,J,K,L,M
Clover, crimson crimson	*Trifolium incarnatum*		X							X	X		5.5 to 7.0		P,Q,V,Y,Z,ZA	
Clover, alsike	*Trifolium hybridum*						X			X		X		18-20+		A,G,H,J,F
Clover, white	*Trifolium repens*						X			X		X		18-20+		A,B,D,G,H,I
Medic, black	*Medicago lupulina*						X			X	X			14-20+		A,G,H,I

* See figures 4-35 and 4-36

TABLE 4-32

CHARACTERISTICS AND SUITABILITY OF GRASSES RECOMMENDED FOR ESTABLISHING GROUND COVER

No.[a]	Name: Common	Name: Scientific	Region/Soil: Humid: Acid	Region/Soil: Humid: Excessively Drained	Region/Soil: Humid: Poorly Drained	Region/Soil: Humid: Saline-Alkaline	Region/Soil: Arid and Semiarid: Excessively Drained	Region/Soil: Arid and Semiarid: Poorly Drained	Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance[a]	Annual Precipitation Tolerance Range, in.[b]	Recommended Plant Growth Regions[c]: Humid	Recommended Plant Growth Regions[c]: Arid and Semiarid
1	Wheatgrass, crested	*Agropyron cristatum*					X				X		X		10-17		A,D,E,G,H,I,J
2	Wheatgrass, "Fairway" crested	*Agropyron cristatum*, var "Fairway"					X				X		X		10-17		A,D,E,G,H,I,J
3	Wheatgrass, thickspike	*Agropyron dasystachyum*					X	X			X		X		10-17		A,D,G,H,I,J
4	Wheatgrass, standard crested	*Agropyron desertorum*				X	X		X		X		X		10-17		A,D,E,G,H,I,J
5	Wheatgrass, tall	*Agropyron elongatum*				X		X	X		X	X			14-20+		A,B,D,E,F,G,H, I,J,K,L,M,N
6	Wheatgrass, streambank	*Agropyron riparium*				X					X	X			11-19		A,D,G,H,I,J,L
7	Wheatgrass, Siberian	*Agropyron sibiricum*					X		X		X		X		10-16		A,D,E,G,H,I,J
8	Wheatgrass, slender	*Agropyron trachycaulum*				X					X		X		15-20+		A,B,D,E,G,H, J,L
9	Wheatgrass, pubescent	*Agropyron trichophorum*					X		X		X		X		12-18		A,B,D,E,F,G,H, J,L,N
10	Foxtail, meadow	*Alopecurus pratensis* var. "Garrison"						X			X		X	6.0	20+		D,E,H
11	Bluestem, big	*Andropogon gerardii*						X		X			X		16-20+		A,B,C,E,F
12	Bluestem, sand	*Andropogon hallii*					X			X			X		14-20+		A,B,C,E,K
13	Grama, sideoats	*Bouteloua curtipendula*					X			X			X	7.5	12-20+		A,B,C,E,F,K

[a]pH values listed refer to the lowest pH value at which the species will grow sufficiently to provide an acceptable ground cover.

[b]Range in precipitation applies only to arid and semiarid regions.

[c]Letters refer to areas shown in Figures 4-35 and 4-36.

(continued)

TABLE 4-32 (continued)

No.	Common Name	Scientific Name	Region/Soil: Humid: Acid	Humid: Excessively Drained	Humid: Poorly Drained	Arid and Semiarid: Saline-Alkaline	Arid and Semiarid: Excessively Drained	Arid and Semiarid: Poorly Drained	Arid and Semiarid: Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance	Annual Precipitation Tolerance Range, in.	Recommended Plant Growth Regions: Humid	Recommended Plant Growth Regions: Arid and Semiarid
14	Grama, black	*Bouteloua eriopoda*					X				X		X		9-18		B,C,F,I,K
15	Grama, red	*Bouteloua trifida*					X			X			X		12-20+		C,F,K
16	Brome, California	*Bromus carinatus*, var. "Cucamonga"					X				X	X		5.5	10-20+		M, & N. Pacific coast
17	Brome, blando	*Bromus mollis*					X				X	X			12-20+		M
18	Bromegrass, red	*Bromus rubens*					X				X	X			14-20+		G,H,I,L,M,N
19	Buffalograss	*Buchloe dactyloides*				X				X			X		12-20+		A,B,C,K
20	Sandreed, prairie	*Calamovfila longifolia*					X			X			X		10-20+		A,B,J
21	Windmillgrass, hooded	*Chloris cucullata*					X			X			X		10-18		A,B,C,K
22	Saltgrass (inland and coastal)	*Distichlis stricta*				X			X	X			X		14-20+		A,B,G,H,I,J, K,M,N
23	Wildrye, basin	*Elymus cinereus*				X		X	X		X		X		14-20+		A,D,E,G,H,I,J,L
24	Wildrye, mammoth	*Elymus giganteus*				X	X		X		X		X		10-16		A,E,G,H,I,J,K
25	Wildrye, blue	*Elymus glaucus*						X			X		X				A,D,E,F,G,H,J, & north L
26	Wildrye, Russian	*Elymus junceus*				X					X		X		13-20+		A,D,E,F,G,H,I,J
27	Wildrye, beardless	*Elymus triticoides*				X		X			X		X		16-20+		A,E,G,H,I,J,K, L,M
28	Lovegrass, Boer	*Eragrostis chloromelas*				X			X	X			X		12-19		G,K,N
29	Lovegrass, Lehmann	*Eragrostis lehmanniana*					X			X			X	7.5	10-18		B,C,K,M
30	Lovegrass, sand	*Eragrostis trichodes*					X		X	X			X		16-20+		A,B,C
31	Fescue, Arizona	*Festuca arizonica*, var. "Redondo"					X				X		X		16-20+		F,J
32	Fescue, hard	*Festuca ovina duriuscula*					X				X		X		13-20+		A,D,E,G,H,I,L

(continued)

TABLE 4-32 (continued)

No.	Name: Common	Name: Scientific	Region/Soil: Humid: Acid	Humid: Excessively Drained	Humid: Poorly Drained	Arid and Semiarid: Saline-Alkaline	Arid and Semiarid: Excessively Drained	Arid and Semiarid: Poorly Drained	Arid and Semiarid: Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance	Annual Precipitation Tolerance Range, in.	Recommended Plant Growth Regions: Humid	Recommended Plant Growth Regions: Arid and Semiarid
33	Mesquite, curly	*Hilaria belangerii*					X			X			X		14-20+		B,C,F,K,N
34	Tobosa	*Hilaria mutica*						X		X			X		12-18		B,C,F,K,N
35	Galleta, big	*Hilaria rigida*				X				X			X		9-14		F,N
36	Sprangletop, green	*Leptochloa dubia*					X			X			X		12-20+		B,C,K
37	Wiwerna (or Swiss ryegrass)	*Lolium rigidum*				X			X		X	X			10-20+		M-
38	Ricegrass, Indian	*Oryzopsis hymenoides*					X				X		X		8-16		M-
39	Smilograss	*Oryzopsis miliacea*					X				X		X		16-20+		M-
40	Kleingrass	*Panicum coloratum*				X				X			X		18-20+		East, central, and west central Texas
41	Hardinggrass	*Phalaris tuberosa, Stenoptera*					X				X		X		16-20+		M. & central Texas
42	Bluegrass, big	*Poa ampla*					X				X		X		12-20+		D,E,G,H,I,L
43	Blowoutgrass	*Redfieldia flexuosa*					X		X	X			X		8-16		A,B,F
44	Sacaton, alkali	*Sporobolus airoides*				X	X	X			X		X		10-20+		A,B,C,D,E,F,G,H,I,J,K,-N
45	Dropseed, spike	*Sporobolus contractus*					X			X			X		10-18		B,F,I,J,K,N
46	Dropseed, sand	*Sporobolus cryptandrus*					X		X	X			X		10-18		A,B,C,E,F,G,H,I,K,N
47	Dropseed, mesa	*Sporobolus flexuosus*					X		X	X			X		8-12		C,I,K
48	Dropseed, giant	*Sporobolus giganteus*					X		X	X			X		8-12		B,C,F,I,K
49	Needle-and-thread	*Stipa comata*					X				X		X		10-16		A,B,D,E,F,G,H,I,J,K
50	Cottontop, Arizona	*Trichachne californica*					X			X			X		12-20+		B,C,F,K,N

(continued)

TABLE 4-32 (continued)

No.	Name: Common	Name: Scientific	Region/Soil: Acid	Region/Soil: Humid: Excessively Drained	Region/Soil: Humid: Poorly Drained	Region/Soil: Arid and Semiarid: Saline-Alkaline	Region/Soil: Arid and Semiarid: Excessively Drained	Region/Soil: Arid and Semiarid: Poorly Drained	Region/Soil: Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance	Annual Precipitation Tolerance Range, in.	Recommended Plant Growth Regions: Humid	Recommended Plant Growth Regions: Arid and Semiarid
51	Trichloris, twoflower	*Trichloris crinita*					X			X			X		8-16		C,K,N
52	Wheatgrass, western	*Agropyron smithii*		X		X	X	X	X		X		X	4.5	14-20+	O,P,S,U,V,X	A,B,D,E,F,G,H, I,J,K,L
53	Bluestem, little	*Andropogon scoparius*		X			X		X	X			X	6.0	16-20+	O,P,Q,R,S,T,U,V,W, X,Y,Z	A,B,C,E,F,K
54	Oats, common	*Avena sativa*	X								X	X		5.5		O,P,Q,R,S,T,U,V,W,X, Y,Z	A,B,C,D,E,F,G, H,I,J,K,L,M
55	Grama, blue	*Bouteloua gracilis*		X					X	X			X	6.0	9-18	Q,R,T,U,W,X	A,B,E,F,J,K
56	Brome, smooth	*Bromus inermis*	X	X					X		X		X	5.5	17-20+	O,P,R,S,T,U,V,W,X, Y,Z	A,B,D,E,G,H, I,J,K
57	Windmillgrass, tumble	*Chloris verticillata*	X	X						X			X	5.0		P,Q,S,V,X,Y	B,E,F
58	Bermudagrass, common and cultivars	*Cynodon dactylon*	X	X		X		X		X			X	4.5	16-25+	Q,X,Y,Z,ZA	A,B,C,K,M,N
59	Lovegrass, plains	*Eragrostis intermedia*		X			X			X			X	5.0	14-20+	Q,Z	B,C,F,K
60	Plumegrass, bent-awn	*Erianthus contortus*			X					X			X			Q,Y,Z	
61	Fescue, tall	*Festuca arundinacea* and cultivars	X	X	X	X		X	X		X		X	5.0	18-20+	O,P,R,S,T,U,V,W,X,Y, Z, & N. Pacific coast	A,B,G,H,I,J,L, M,N
62	Switchgrass	*Panicum virgatum*	X		X	X		X	X	X			X	5.0	18-20+	O,P,Q,R,S,T,V,X,Y	A,B,C,K
63	Millet, pearl	*Pennisetum americanum*															
64	Canarygrass, reed	*Phalaris arundinacea*	X		X	X		X			X		X	5.0	18-20+	O,P,R,S,T,U,V,W,X, & N. Pacific coast	A,B,E,F,G,H,I, J,L,M
65	Indiangrass	*Sorghastrum nutans*		X	X			X		X			X	5.5	18-29+	P,Q,S,V,X,Y	A,B,C,F,K
66	Redtop	*Agrostis alba*	X	X	X				X		X		X	4.0		O,P,R,S,T,U,V,W,X,Y	
67	Bluestem pinehill	*Andropogon divergens*		X						X			X	4.5		Q,V,Z	

(continued)

TABLE 4-32 (continued)

No.	Name: Common	Name: Scientific	Region/Soil: Humid: Acid-	Region/Soil: Humid: Excessively Drained	Region/Soil: Humid: Poorly Drained	Region/Soil: Arid and Semiarid: Saline-Alkaline	Region/Soil: Arid and Semiarid: Excessively Drained	Region/Soil: Arid and Semiarid: Poorly Drained	Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance	Annual Precipitation Tolerance Range, in.	Recommended Plant Growth Regions: Humid	Recommended Plant Growth Regions: Arid and Semiarid
68	Bluestem, splitbeard	Andropogon ternarius		X						X			X	4.5		P,Q,V,X,Y,Z	
69	Broomsedge	Andropogon virginicus			X					X			X	5.0		Y,Z,ZA	
70	Oatgrass, tall	Arrhenatherum elatius		X					X		X		X	5.0		O,P,R,S,T,U,V,W,X, & N. Pacific coast	
71	Bluestem, King Ranch	Bothriochloa ischaemum var. sengarica		X			X			X			X			Q,Z	
72	Millet, browntop	Brachiaria ramosa			X					X		X		5.0		Region ZA mostly	
73	Brome, field	Bromus arvensis		X					X		X		X	6.0		O,P,R,S,T,U,V,W,X,Y	
74	Rhodesgrass	Chloris gayana	X			X				X			X	4.0		Y,Z,ZA	
75	Orchardgrass	Dactylis glomerata		X							X		X	5.0		O,P,R,S,T,U,V,W,X,Y	
76	Lovegrass, weeping	Eragrostis curvula	X	X					X	X			X	4.5		P,Q,V,X,Y,Z	
77	Lovegrass, purple	Eragrostis spectabilis		X						X			X	4.5		O,P,Q,R,S,T,U,V,W, X,Y,Z	
78	Centipedegrass	Eremochloa ophiuroides		X						X			X	4.5		Q,Y,Z,ZA,ZB	
79	Fescue, creeping red and cultivars	Festuca rubra		X	X						X		X	5.0		O,P,R,S,T,U,V,W,X,Y	
80	Barley	Hordeum vulgare	X			X					X	X		5.5		O,P,Q,R,S,T,U,V, W,X,Y,Z	F,N
81	Ryegrass, annual	Lolium multiflorum	X	X	X				X		X	X		5.5		O,P,Q,R,S,T,U,V,W,X, Y,Z, & N. Pacific coast	
82	Ryegrass, perennial	Lolium perenne	X	X	X				X		X		X	5.5		O,P,R,S,T,U,V,W,X,Y	
83	Deertongugrass	Panicum clandestinum, var. "Tioga"	X	X					X	X			X	3:8		-S,U,V,W,X,Y	

(continued)

TABLE 4-32 (continued)

No.	Name: Common	Name: Scientific	Region/Soil: Humid: Acid	Region/Soil: Humid: Excessively Drained	Region/Soil: Humid: Poorly Drained	Region/Soil: Arid and Semiarid: Saline-Alkaline	Region/Soil: Arid and Semiarid: Excessively Drained	Region/Soil: Arid and Semiarid: Poorly Drained	Region/Soil: Arid and Semiarid: Wind Erosion Control	Season: Warm	Season: Cool	Longevity: Annual	Longevity: Perennial	Lower pH Tolerance	Annual Precipitation Tolerance Range, in.	Recommended Plant Growth Regions: Humid	Recommended Plant Growth Regions: Arid and Semiarid
84	Panicum, spreading	Panicum rhizomatum		X						X			X	4.5		Y,Z,ZA,ZB	
85	Paspalum, Florida	Paspalum floridanum			X					X			X			Y,Z,ZA except Gulf Coast marshes	
86	Bahiagrass	Paspalum notatum	X	X					X	X			X	4.5		Q,Y,Z,ZA	
87	Timothy	Phleum pratense	X		X						X		X	4.5		O,P,R,S,T,U,V,W,X,Y	
88	Bluegrass, Canada	Poa compressa	X	X	X								X	4.5		O,R,S,T,U,W,X	
89	Bluegrass, Kentucky	Poa pratensis			X						X		X	5.5		O,P,R,S,T,U,V,W,X	
90	Rye, and cultivars	Secale cereale	X		X				X		X	X		5.5		O,P,Q,R,S,T,U,V,W, X,Y,Z	
91	Millet, foxtail	Setaria italica	X							X		X		5.5		O,P,Q,R,S,V,Y	
92	Johnsongrass	Sorghum halapense		X						X			X	6.0		Y,Z,ZA	
93	Sorghum X Sudan hybrids	Sorghum spp.	X	X						X		X		4.5		O,P,Q,R,S,T,U,V,W,X, Y,Z,ZA, & N. Pacific coast	
94	Sudangrass	Sorghum sudanense	X	X					X	X		X		5.5		O,P,Q,R,S,T,U,V,W,X, Y,Z,ZA, & N. Pacific coast	
95	Wheat and cultivars	Triticum aestivum	X								X	X		4.5		O,P,Q,R,S,T,U,V,W, X,Y	
96	Zoysiagrass	Zoysia japonica	X	X	X					X		X		5.0		P,Q,S,V,X,Y,Z, & N. Pacific coast	
97	Zoysiagrass, Meyers	Zoysia japonica, var. "Meyers"	X	X						X		X		5.0		Q,V,Y,Z,ZA, & N. Pacific coast	
98	Zoysiagrass, Emerald	Zoysia japonica X Zoysia tenuifolia	X	X						X		X		5.0		Q,V,Y,Z,ZA, & N. Pacific coast	

- Adaptability to climatic conditions (sunlight exposure, temperature, wind exposure, rainfall, drought) found at the site
- Tolerance to gases and organic decomposition products from buried waste
- Resistance to fire, insect damage, diseases, and other pests
- Compatibility with the principles of secondary succession, and of land management objectives (Mueller-Dombois and Ellenberg, 1974)
- Compatibility with other plants selected for use on the same area
- Ability to propagate themselves (either by seed or vegetatively)
- Short- and long-term maintenance requirements and costs

To minimize the possibility of failure in establishing an erosion-control cover and at the same time reduce post-establishment maintenance requirements, one must select grasses and legumes that are adaptable to the soil conditions found at the site. This is especially important if the waste cover system establishes an artificial soil profile. For example, the use of an impermeable layer over the waste can create a shallow perched water table in the overlying soil profile. A sloping cover system could result in the upper portion of the slope drying out faster, while the lower portion of the slope would be wetter for longer periods of time. Consequently vegetation on the upper slopes will need to be more drought-resistant, while the lower-slope vegetation will need to tolerate prolonged wet periods.

The possibility of marked differences in soil moisture regimes within a waste-site cover system should be given careful consideration. There are ways to reduce the range of extreme soil moisture conditions across a waste site (e.g., application of organic matter to the upper slope to retain more soil moisture for a longer time period). The information obtained during the preliminary waste site characterization can indicate monthly rainfall distribution and those plant species that have tolerated wet and dry soil moisture conditions at the site. These existing plant species will invade the cover system and attempt to establish themselves in any area that has a suitable soil moisture regime to which they are adapted. Plant species observed in wet areas surrounding the waste site will eventually colonize any wet areas created in the cover system and having suitable soil conditions for growth.

4.9.3.2 Criteria for Selecting Shrubs and Trees

Since a major objective of the cover system is to isolate the waste from percolating water, the use of shrubs and trees may have serious limitations. There is insufficient information at present to indicate appropriate shallow-rooted shrubs and trees. Most shrubs and trees will extend their root systems deep into the soil profile and can potentially penetrate any impermeable barrier covering the waste. The penetration of tree or shrub roots through

this protective barrier will allow water to percolate into the waste, which is highly undesirable. While chemobarriers (discussed in section 4.8) theoretically can be placed on the impermeable barrier covering the waste and should inhibit shrub or tree roots from penetrating into the waste, these chemobarriers have not been adequately field tested on shrubs and trees.

One application for which shrubs and trees might be considered is on the side slopes of waste piles. See for example the Kin-Buc Landfill in Appendix B, "Case Histories." On side slopes, impermeable membranes are inappropriate because of the threat of sliding of the overlying soil. Rill erosion, caused by direct raindrop attack, is a problem on these slopes. Ground-cover shrubbery, by intercepting raindrops, might minimize such erosion. Some penetration of the waste by shrubbery roots would occur, but owing to the steep slope, the great majority of precipitated water will run off rather than enter the ground.

Given these limitations, the following criteria should be considered in selecting shrubs and trees for use in vegetative covers at waste sites (adapted from McKell, 1975):

- Availability in needed quantity and appropriate time frame.
- Ability to produce shallow extensive root systems in order to exploit the entire layer of soil cover material for nutrients and moisture.
- Ability to become quickly established.
- Tolerance of acid, saline, sodic, wet and droughty compacted (clayey) soil environments.
- Compatibility with the principles of secondary succession.
- Ability for vigorous growth after relief of moisture stress, and coppice formation and regrowth after physical damage to roots/shoots.
- Ability to reproduce by natural cloning and/or by seeds.
- Ability to create islands of soil fertility by fostering an accumulation of organic matter, detritus, and nutrients.
- Resistance to fire, insects, diseases, animals and other pests.
- Compatibility with the erosion-control grasses and legumes used to initially stabilize the cover.
- Tolerance to gases and organic decomposition products from buried wastes.
- Relative maintenance requirements and costs.

The permanent shrub and tree species that are finally selected must be adapted to the soil conditions found at the site.

4.9.3.3 Breeding and Selecting Plants to Tolerate Stress

Perhaps the most effective strategy in establishing a stable vegetative cover is the selection and genetic manipulation of plant species for tolerance to various mineral and associated stresses at a waste site (Baker, 1976). Current thinking on the tailoring of plants to fit the soil condition is that soil test calibrations are needed for selected plant species and cultivars, in concert with the determination of those soil limitations that may be economically modified or conditioned to permit the growth of plant species that have been selected or bred for tolerance to various soil conditions (Baker, 1976).

Up to the present time, notable success has been reported in selecting lovegrasses having tolerance to toxic levels of soil aluminum (Foy et al., 1980), in developing metal-tolerant varieties of red fescue and common bent (Smith and Bradshaw, 1972), and in the breeding and selection of barley varieties having tolerance to very high levels of salinity (Epstein, 1977). Many of the plant species listed in Tables 4-31 and 4-32 have been developed through genetic manipulation and natural selection. Those plant species have been tailored or selected to thrive in the soil condition indicated.

It is most critical that the soil cover environment be accurately known in order to select the most appropriate plant species, and appropriate rhizobium species for legumes, for the site.

4.9.3.4 Source of Seed

Certified named varieties of adapted seeds should be used when available. The source of adapted seeds should correspond to the SCS land resource area similar to that occupied by the waste site, and, in the southwestern United States, not in excess of approximately 300 miles south or about 200 miles north of the site.

4.9.3.5 Use of Single Species Versus Mixtures

Several factors influence the selection of a single species or mixtures. These factors can include the degree of maintenance required, the desire to have the planting visually compatible with the surrounding vegetation and the long-term planned use of the site. Single grasses or mixtures of grasses normally will require more maintenance nitrogen fertilizer than mixtures of grasses and legumes. Legumes fix atmospheric nitrogen in their roots and release the nitrogen in a form available to companion grasses in the mixture. The creation of nitrogen cycles in derelict land has been successfully promoted in Europe (Bradshaw et al., 1982). The application of these principles to waste cover systems should be considered. Legumes can readily accumulate 45-135 lb N/acre annually if provided with appropriate conditions (Bradshaw et al., 1982). The use of legumes in mixtures with grasses will therefore reduce the need and cost of expensive supplemental nitrogen fertilizers. In essence,

9 3 1 2 9 0 4 1 1 2 9

a self-sustaining vegetative cover could be established at the waste site. While nitrogen needs can be satisfied with legumes included in grass mixtures, there may still be a need for maintenance applications of lime and phosphorus fertilizer to sustain a healthy vegetative cover if these materials are limiting in the soil cover (Bradshaw et al., 1977). Many legumes are deep-rooted plants. Consequently, caution must be taken to control deep root penetration of the cover system into the waste material. Use of a biotic barrier (sec. 4.8) may be required to control legume root penetration. Excellent advice on grass-legume mixtures can be obtained from SCS plant material specialists and U. S. Forest Service reforestation specialists.

4.9.3.6 Use of Adapted Native Versus Introduced Plant Species

Native species should be given preference and used rather than introduced species if they satisfy waste-site management objectives and can adequately vegetate soil cover material used at the waste site. This choice is valid for waste sites so long as it is consistent with the major criteria listed earlier.

4.9.3.7 Undesirable Species

Care should be taken in not selecting herbaceous and woody species whose growth habits are incompatible with the long-term management of the site, or which, upon escape (i.e., as airborne seeds), inadvertently become undesirable weeds in adjacent areas. Nonweedy species that are adapted to the soil environment at the waste site should be used (U. S. Department of Agriculture, 1973). Potentially weedy plants should only be used in areas that are far removed from prime farmlands.

4.9.3.8 Other Selection Factors

The following items should also be considered in plant selection:

- Potential fire risk of plant materials
- Adaptability to south-slope exposures versus north-slope exposures (aspect or exposure affects solar radiation loads, light quality, day length, and growing season length)
- Presence of animals and birds that will aid in seed dispersal (e.g., some plant species are totally dependent on animals for seed dispersal)
- Adaptability of plant materials to habitats at increased elevations (generally, as elevation increases, the length of the growing season decreases).

9 3 1 2 9 0 4 1 1 3 0

Adaptability of plant materials to any potential artificial soil profile effects within the cover system at the waste site (i.e., perched water table).

Grasses and forbs are the most effective plant materials for controlling erosion. Trees and shrubs are not very effective in controlling erosion in the early stages because of their initial slow development. But during the middle and late stages of a developing vegetative cover system, the trees and shrubs form a protective canopy and provide necessary buildup of surface organic material (detritus and litter) which is excellent in controlling surface runoff and erosion. In addition, trees and shrubs can be beneficial for screening, wildlife, and forestry purposes (Lee et al., 1984).

4.9.4 Establishment and Maintenance of Vegetation

4.9.4.1 Time of Seeding and Planting

An examination of waste site characterization information dealing with the climatic region of the site and several years of temperature/precipitation records will aid in determining the most favorable seeding and planting periods. This information can be related to the amount of time needed for plant establishment.

Baseline data will help indicate if a climatic region is subject to false plant-growth starts; for example, the region may have early precipitation that wets the soil and initiates seed germination, followed by a long, dry period. Of course this information will be very general, and weather conditions may vary in the planting year under study, thus causing a change in planting times (U. S. Department of Agriculture, Forest Service, 1979).

Irrespective of the climatic region and the waste site, the general rule is to plant erosion-control grasses and legumes immediately ahead of the highest expected rainfall probability. Precipitation probability tables are available for use in the selection of a seeding date compatible with plant growth (i.e., during the frost-free times). Additional assistance can be obtained from the Plant Materials Specialists of the Soil Conservation Service and local agricultural county agents in appropriate regions.

Grasses and legumes used for vegetative covers are established by direct seeding on a properly prepared seedbed. Seeding application rates are given according to State in Lee et al. (1984). Annual species are quick to establish a cover and will be effective for one year. Perennial species should also be mixed into the seed application. They are slower to establish but will continue regrowth year after year. Woody plants, such as shrubs and trees, are established by seedling transplants. However, some woody species can be seeded directly. The soil material used for covering the waste site should be analyzed to determine the proper lime and fertilizer requirements according to the local State soil testing laboratory.

If the optimum planting dates are exceeded because of extreme weather or other conditions, the area should be seeded to one or more fast-growing annual species such as wheat, rye grass, millet, rye, and grain sorghums. Additional information on specific considerations within each of the plant growth regions can be found in Lee et al. (1984).

4.9.4.2 Irrigation as a Temporary Measure

Irrigation should be used only as a temporary measure to ensure the initial establishment of herbaceous and woody vegetation in arid, semiarid, and subhumid regions. Temporary irrigation can also be used to aid in leaching salts from the saline soils found in arid, subhumid, and humid climates. The amount and frequency of irrigation depends on the availability of funds and labor, the water requirements of the particular plant species, the amount and intensity of natural precipitation, and the chemical and physical makeup of the soil materials at a specific waste site. Details on the particular irrigation and management practices for saline soils are presented in Richards (1969) and U. S. Department of Agriculture, Forest Service (1979).

4.9.4.3 Methods of Seeding and Planting

Methods of seeding erosion-control vegetation on waste sites will vary depending on topography, type of vegetation, stoniness of soil surface, and equipment availability. Currently used seeding methods and their specific suitability are:

- Hydroseeders are very useful for applying seed, fertilizer, and mulch on steep slopes and in other areas where equipment accessibility is limited.
- Cyclone seeders are well suited for broadcasting seed on level areas. Germination can be increased by limiting equipment travel over seeded areas.
- Grass or grain drills are limited to rolling or level terrain that is relatively free of stones. The Rangeland drill is sturdier than conventional drills and provides better and longer performance on critical area soils.
- Rear-mounted blowers can be attached to lime trucks to spread both seed and fertilizer on steep slopes and other inaccessible areas.
- Sprigging is used for certain grass species to establish vegetative cover more rapidly than would be possible using seed.
- Hand planting generally is used when bare-root seedlings of trees and shrubs are planted. The method is time-consuming and therefore costly.

9 3 1 2 9 0 4 1 1 3 2

(1) Arid and semiarid climates. Seeds may be planted by either drilling or broadcasting, but under semiarid and arid conditions drilling is recommended for the following reasons:

- The seed is covered to a proper depth and protected from the environment
- The seed is uniformly distributed
- Rate of seeding is controlled
- Soil firming can be done with the packer wheels attached to the drill (U. S. Department of Agriculture, Forest Service, 1979).

In arid and semiarid climates, broadcasting is considered less efficient because the seeds often perch on top of the soil where germination and establishment are difficult, if not impossible. Rodents and birds may pick up broadcast seeds and eat them or carry them away to a seed cache. When seed is broadcast the soil should always receive some mechanical treatment to give suitable seed coverage, unless the bed is loose so that the natural sloughing of soil will cover the seed. Planting should be done on the contour to trap available moisture and prevent erosion (Lee et al., 1984). Numerous types of drills and broadcasters are on the market for use in arid regions. Selection of specific equipment will depend on their availability, capability, characteristics of the site, and treatment required. Further details on drills and other equipment for arid and semiarid regions are listed in U. S. Department of Agriculture, Forest Service (1979).

(2) Humid climates. A good seedbed is essential for the successful establishment of seeded vegetation, both herbaceous and woody. Except for the winter period, an ideal situation is to seed the soil immediately after grading, thereby taking advantage of a ready-made seedbed. For preparing a seedbed, "front blading" with a bulldozer provides some advantage over "back blading" because of impressions left in the soil by the dozer tracks provide microsites that favor seed germination and seedling establishment. However, with either method of grading, it is best to seed immediately after the grading, because most cover soil materials will crust over or harden after they are rained on and dry out (Lee et al., 1984).

There is no "best" method for applying seed. The main requirement is that the seed be evenly distributed on a good seedbed. The hydroseeder is widely used and desirable because it can place seed on outslopes and highwalls where most other types of seeders cannot reach. The term hydroseeding means the hydraulic application of a slurry of plant seeds and water to problem soils. However, for seeding benches and leveled areas, a cyclone seeder or a grass drill can be just as effective. In fact, spreading seed "dry" has some advantages in that the entire load in the seeder is payload and not mostly water as with the hydroseeder. Dry-mixing seed and fertilizer together and spreading with a conventional lime-spreading truck is an efficient method for covering large areas. The Estes One-Way Blower attached to lime trucks increases their versatility and "reach" on large areas. Some problem may occur in calibrating the rate of dispersal so that both seed and fertilizer are applied at about

the proper rates. However, this equipment has been successfully used for seeding and fertilizing strip mines in eastern Kentucky.

Soils that are free of stones and level enough for use of farm equipment may be seeded with a grass or grain drill. One advantage of using a drill is that all of the seed is placed in the soils and covered. Thus, less seed is needed because most of the seed is placed in a microenvironment that favors germination and seedling establishment. Tillage or scarification of a seedbed usually is not necessary prior to seeding with a drill.

Details for planting shrubs and trees in humid climates are given in Lee et al. (1984). Additional information can be obtained from the USDA, Forest Service and State Forestry Departments.

4.9.4.4 Mulching and Chemical Stabilization

Mulching and chemical stabilization are two major types of short-term, or temporary, nonvegetative soil stabilization. Both are employed to provide protection against excessive soil erosion for periods of less than one year.

Mulching is essential on most waste cover soils and especially on slopes steeper than 3:1. Figure 4-37 illustrates the relationship between surface slope and potential for soil erosion.

The application of plant residues or other suitable mulch materials to the soil surface functions to:

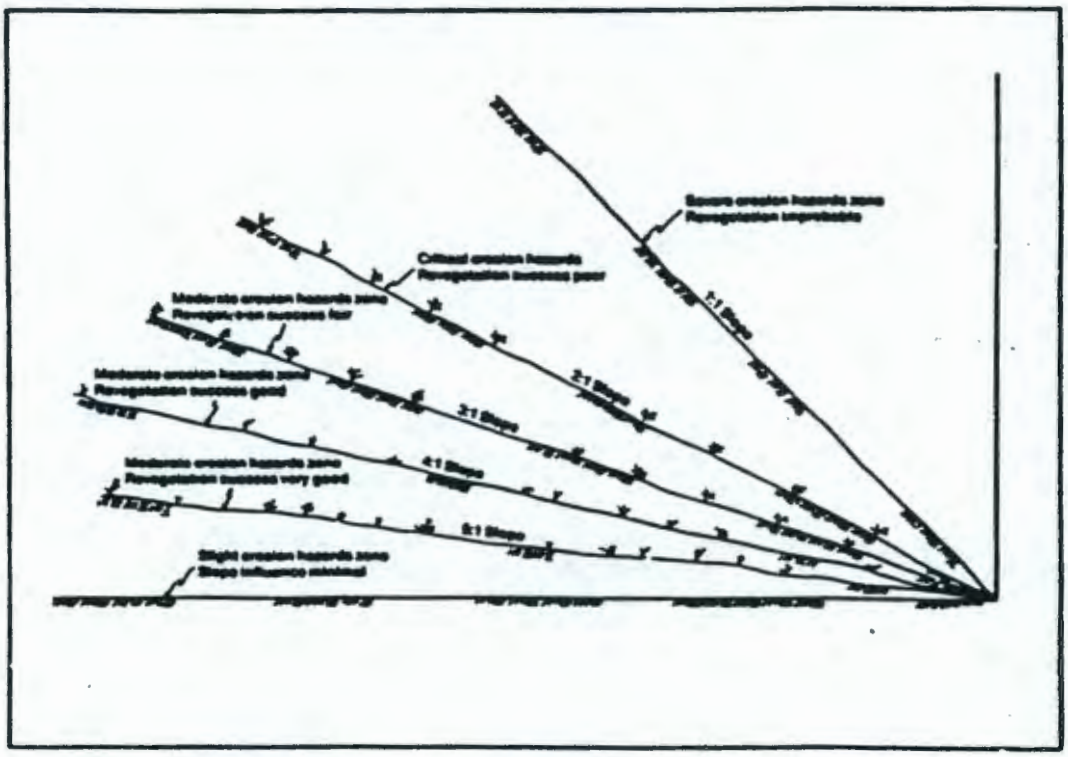
- Prevent erosion, both by water and wind
- Prevent surface compaction or crusting
- Facilitate infiltration
- Inhibit evaporation (which may also slow upward movement of salts through soils)
- Provide proper soil temperatures
- Be compatible with plant development, improve germination conditions, protect seedlings
- Possibly add desired seeds while acting as a mulch
- Reinoculate microorganisms into excavated materials

The effectiveness of any mulch depends upon many factors, including the physical and chemical properties of the soil, the land-forming or cultural practices, species to be seeded, and the characteristics of the mulch itself, such as its color, roughness, and manner of application (Lutton, Regan, and Jones, 1979). The effect of color and roughness are directly related to the

9 3 1 2 9 0 4 1 1 3 4

FIGURE 4-37

INFLUENCE OF SLOPE ON REVEGETATION
(FROM NEVADA STATE CONSERVATION COMMISSION)



radiation balance at the soil surface and, consequently, the heat transfer into and out of the soil. Slope and orientation of the soil surface also influence the solar energy input. Other factors determining mulch efficacy are steepness and length of slope, soil texture and depth, rate of application of mulch, and the weather before, during, and after mulch application. Selection depends upon characteristics of the area to be stabilized and the availability, cost, and properties of the mulch material (Lutton, Regan, and Jones, 1979). Several of the more common and effective mulches and their applications are listed in Tables 4-33 and 4-34 (Lee et al., 1984).

4.9.4.5 Organic Mulches

Mulches of organic materials such as straw, hay, woodchips, wood fiber, and other conventional short-term materials are the most popular means of providing short-term soil stabilization. Mulch is used in the establishment of a vegetative ground cover to protect the seedbed from excessive erosion prior to germination of the seeds and until the new vegetation is sufficiently

TABLE 4-33

GUIDE TO SHORT-TERM MULCH MATERIALS, RATES, AND USES

Mulch Material	Quality Standards	Application Per 1000 sq. ft.	Application Per Acre	Depth of Application	Advantages	Disadvantages	Remarks[a]
Sawdust, green or composted	Free from objectionable coarse materials	83-500 cubic feet	--	1"-7"	Protects surface Adds organic matter No weed seeds More fire resistant than straw Long lasting	Shavings and sawdust blow Nitrogen deficiency Packing may occur resulting in less aeration May float on running water	Most effective as a mulch around ornamentals, small fruits, and other nursery stock. Special application rates - fruit trees 5-7"; vegetables and flowers 2-3"; blackberries and raspberries 4-7"; strawberries 3". Good resistance to wind blowing. Requires 30-35 lbs. N/ton to prevent N deficiency while decaying mulch. One cubic foot weighs 24 pounds.
Wood chips	Green or air dried. Free from objectionable coarse materials	500-900 lbs.	10-15 tons	2"-7"	Easy to apply Chips resistant to wind movement	May prevent precipitation from reaching soil	Has about the same use and application as sawdust, but requires less N/ton (10-12 lbs.). Resistant to wind blowing. Decomposes slowly.
Wood excelsior	Green or air dried burred wood fibers .024" x .041" x 4"	90 lbs. (1 bale)	2 tons	--			Effective for erosion control. Tie-down needed on windy sites. Decomposes slowly. Packaged in 80-90 lb. bales.
Wood fiber cellulose (partly digested wood fibers)	Usually dyed green. No growth organism inhibiting factors. Air dried 30% fibers 1.7 mm	25-30 lbs.	1000-1500 lbs.	--			When used for erosion control on critical areas double application rate. Apply with hydromulcher. No tie-down required. Packaged in 100 lb. bags. Has not been very satisfactory for establishing seedings on arid sites.
Compost or manure	Well shredded, free from excessive coarse material	400-600 lbs.	8-10 tons	--	Can protect soil surface and adds nutrients, such as N, P, K, S	When used alone, it becomes wet, then dry, can lose much of N through volatilization of ammonia	Use a strawy manure when erosion control is needed. May create problems with weeds. Excellent moisture conserver. Resistant to wind blowing.
Cornstalks or sorghum stover, shredded or chopped	Air dried, shredded into 8" to 12" lengths	150-300 lbs.	4-6 tons	--			Effective for erosion control, relatively slow to decompose. Excellent for mulch crop on fields. Has about the same value as a cover crop. Resistant to wind blowing
Grass hay or grain or straw	Air dried, free from undesirable seeds and coarse materials	75-100 lbs., 2-3 bales	1.5-2.5 T. 90-120 bales	Lightly covers 75 to 90% of surface	Generally most economical Usually satisfactory under many circumstances	Weed seeds usually present; even hay seeds may be considered a weed on a particular site Straw may "wick-out" moisture from soils in very dry conditions, thus resulting in poor germination and seedling establishment	Use straw where mulch effort to be maintained for more than 3 months. Subject to wind blowing unless kept moist or tied down. Most common and widely used mulching material. Good for erosion control in critical areas. Anchor mulch, especially on slopes by crimping, or using plastic meshes, jute, chemical tackifiers. Long-stemmed best, especially for crimping. Uniform application important. Can be spread with modified farm manure spreader.
In situ mulches (cereal grains or summer annual crops like wheat, barley, or rye)					Produces quick cover to stabilize disturbed areas. Provides uniform mulch. More economical than artificially applied mulching materials.		Fall crops killed with herbicides in spring before maturity, summer annuals killed by frost in fall. Interseed with permanent grasses and legumes species. Produces up to 7.4 Tons dry matter.

(continued)

TABLE 4-33 (continued)

Mulch Material	Quality Standards	Unit Size	Unit & Weight	Area Covered Per Unit	Advantages	Disadvantages	Remarks[a]
Mats & Netting:					Especially useful on steep slopes Mats good in high wind areas	Expensive: 4-5 times more than tacked straw High labor input for anchoring Not effective on rough surfaces or rocky areas Erosion from beneath may be a problem	Used only on limited critical areas because of cost.
Twisted kraft paper yarn	Plain weave, warp 7 per inch, filling 4 per inch selvage edge with polypropylene filament	45" x 250 yds.	Roll 100 lbs.	312½ sq. yds.			Used to hold seed and aid in germination without mulch. Tie down according to manufacturing specifications. Not effective in seeding establishment on arid sites. Lasts about one year.
Twisted kraft paper yarn	Fungicide treated warp 1.1 pairs/in. filling 2.5/in.	45" x 250 yds.	Roll 80 lbs.	312½ sq. yds.			Use over bare soil or sod to prevent erosion and hold seed. Good for waterways and critical ditch bottoms. Tie down with staples as per manufacturing specifications and on critical areas. Lasts about one year.
Jute, twisted yarn	Undyed, unbleached plain weave. Warp 78 ends/yd. Weft 41 ends/yd	45" x 50 yds. or 48" x 75 yds.	Roll 60 lbs. 90 lbs.	60 sq. yds. 100 sq. yds.			Use without additional mulch. Tie down as per manufacturing specifications. Effective for erosion control in waterways and ditches. Lasts about one year.
Excelsior wood fiber mats	Interlocking web of excelsior fibers w/mulch net backing on one side only.	36" x 30 yds.	Roll --	10½ sq. yds.			Use without additional mulch. Tie down as per manufacturing specifications. Good for establishing seedings on critical areas.
Plastic	2-4 mils	Variable up to 50' wide	--	--	Excellent vapor barrier Good weed control Light colored, perforated, found effective in New Mexico: soil temperature in summer 18°F lower than in soil with no mulch	Labor intensive High cost	Use black for weed control, use white for seeding establishment without organic mulch. Release plastic after seeding is established. Information on temperature effect varies. The materials allow air and water interchange but prevent evaporation of soil moisture. Usually must be renewed each season. Some users place a 1" layer of sand underneath to prevent it from tearing when stepped upon. Must be punctured with frequent small holes for penetration of air and water and weighted down around edges.

[a]All mulches will provide some degree of erosion control, moisture conservation, weed control, and reduction of soil crusting.

TABLE 4-34

MULCH ANCHORING GUIDE

Anchoring Method or Material	Kind of Mulch to be Anchored	How to Apply
MANUAL		
Peg and twine	Hay or straw, pine straw, corn stalks	After mulching, divide areas into blocks appro. 1 sq. yd. in size. Drive 4-6 pegs per block to within 2" to 3" of soil surface. Secure mulch to surface by stretching twine between pegs in crisscross pattern on each block. Secure twine around each peg with two or more turns. Drive pegs flush with soil where mowing and maintenance is planned.
Mulch netting	Hay or straw, shredded sugar cane, pine straw, compost, wood shavings, tanbark, corn stalks	Staple with lightweight paper, jute, wood fiber, or plastic nettings to soil surface according to manufacturer's recommendations.
Soil and stones	Plastic	Plow a single furrow along edge of area to be covered with plastic, fold about 6" of plastic into the furrow and plow furrow slice back over plastic. Use stones to hold plastic down in other places as needed.
Silt	Hay or straw, corn stalks	Cut mulch into soil surface with square-edge spade. Make cuts in contour rows spaced 18" apart.
MECHANICAL		
Asphalt spray (emulsion)	Compost, wood chips, wood shavings, hay or straw	Apply with suitable spray equipment using the following rates: asphalt emulsion 0.04 gallons per sq. yd.; liquid asphalt (rapid, medium, or slow setting) 0.10 gallons per sq. yd.
Wood callulose fiber	Hay or straw	Apply with hydroseeder immediately after mulching. Use 750 lbs. wood fiber per acre.
Pick chain	Hay or straw, manure compost, pine straw	Use on slopes steeper than 3:1. Pull across slopes with suitable power equipment.
Mulch anchoring tool or disk (smooth or notched)	Hay or straw, manure, pine straw	Apply mulch and pull a mulch anchoring tool over mulch. When a disk (smooth) is used, set in straight position and pull across slope with suitable power equipment. Mulch material should be "tucked" into soil surface about 3".
Chemical	Hay or straw	Apply Terra Tack II (45 lbs.) or Aerospray 70 (60 gal/A.) according to manufacturer's instructions. Avoid application during rain. A 24-hour curing period required and soil temperature higher than 45°F.
Sheepsfoot roller or packer	Hay, straw, manure, corn stalks	Pull sheepsfoot roller over the areas after mulch is applied. Can be operated up and down the slope.

established. The mulch provides a favorable environment for seed germination and plant development. Mulches can also be used in place of short-term vegetative stabilization to protect temporarily against excessive soil loss prior to the preparation of a seedbed.

Water-dispersible mulching materials and tacks are used for hydroseeding operations. The most frequently used mulching materials (singly or in various combinations) are wood-cellulose fibers; a 50-50 mix of ground newsprint and corrugated papers (decontaminated of borates); various powdered gums; liquid styrene-butadiene copolymer emulsions; and defibered grass or cereal straws (Kay, 1979; U. S. Environmental Protection Agency, 1976).

In hydroseeding, fertilizers, limestone, mulch materials, and chemical tacks and binders may also be present in the pumped slurry, along with the seeds. Chemical stabilization is discussed in the following section. Comparison of certain water-dispersible mulches and stabilizers is shown in Table 4-35. According to Bradshaw and Chadwick (1980) the wood cellulose fiber ranks equally to jute netting for soil stabilization and to straw mulch for level of persistence.

The term hydromulching applies only when a water-dispersible mulch material is hydraulically spread onto a cover soil material (Kay, 1978; U. S. Environmental Protection Agency, 1976; U. S. Department of Agriculture, Forest Service, 1979). Table 4-36 summarizes information on hydroseeding and hydromulching experience in the state of California. The cost and effectiveness of hydroseeding/hydromulching varies. Alternative methods should be considered, since the most expensive approach is not necessarily the most effective. According to Kay (1978) "straw plus tackifier is more effective for both erosion control and plant establishment than many of the more expensive treatments" (see Table 4-35). Under some conditions, having a rough seedbed or covering the seed may be the best approach to establishment of protective vegetation (Kay, 1978).

The most important consideration for any hydromulching material is that it must stick to the soil and hold the seed on steep slopes against high wind and rainfall intensities (Kay, 1978). But it is equally true that these same qualities may prevent the seed from readily falling into natural depressions (microsites) and becoming covered with soil, thereby promoting a higher stand density (Kay, 1978).

Another problem arises when the germination of legume seeds is inhibited by fertilizers containing moderate to high concentrations of certain soluble salts (e.g., ammonium sulfate and sodium nitrate) in the slurry. When the fertilizers were omitted from the slurry the germination of hydroseeded legume seeds was excellent (Bradshaw and Chadwick, 1980).

The problem of seeds failing to fall into microsites could best be resolved by first broadcasting or drilling the seed, followed by the application of a quality hydromulch (Kay, 1978, p. 6). For the problem of fertilizer inhibition of legume seed germination, the recommended solution was to apply the mineral fertilizer three to six weeks after the initial hydroseeding (Bradshaw and Chadwick, 1980). Other factors generating concern in

TABLE 4-35

COMPARISON OF WATER-DISPERSIBLE MULCHES AND STABILIZERS FOR INITIAL LAND RESTORATION
(Modified from Bradshaw and Chadwick, 1980)

Material	Application Rate[a] (lbs/acre)	Persistence	Stabilization	Soil Moisture Retention	Nutrient	Toxicity
Stabilizer/mulches						
Wood cellulose fibre (as slurry)	890-1780	OO	OOO	O	o	o
Sewage sludge (as slurry)	1780-3560	O	OO	O	O	o
Stabilizers						
Asphalt (as 1:1 emulsion)	670	O	OO	O	o	O
Latex (as appropriate emulsion)	178	O	OO	o	o	OO
Alginate or other colloidal carbohydrate (as emulsion)	178	OO	OO	o	o	o
Polyvinyl acetate (as 1:5 emulsion)	890	OO	OO	o	o	OO
Styrene butiadene (as 1:20 emulsion)	446	OO	OO	o	o	OO

OOO high; OO moderate; O low; o nil

[a] Rates can be varied depending on circumstance-will affect soil water capture and retention and seeding establishment

TABLE 4-36

SUMMARY OF METHODS AND COSTS OF HYDROSEEDING AND HYDROMULCHING IN CALIFORNIA
(Adapted from Kay, 1976)

Treatment	Comments	Preger-mination erosion effect-iveness[a]	Effective-ness on plant establish-ment[a]	Approx. cost per acre $[b]
1. Hydroseeding or hydro-mulching (seed + fer-tilizer) with 500 lb wood fiber, 1,500 gal water/3 acres.	Similar effectiveness to broadcasting seed and fertilizer. Not enough fiber to hold seed in place or produce a mulch effect. Seed distribution would be improved by in-creased volume of water.	1	1-4	250
2. Hydromulching with 1,500 lb wood fiber plus an organic glue: Ecology Control, Terratack III etc. plus seed and fertilizer.	The addition of an organic glue will some-times improve fiber holding and germination. Does not increase labor or machinery cost.	2+	3-6	550-650
3. Hydromulching with 2,000-3,000 lb/acre wood fiber plus seed and fertilizer.	Produces a true mulch effect and some ero-sion protection. Commonly better results than 1,000 lb fiber or fiber plus glue.	2-3	4-7	530-750
4. Seed and fertilizer broadcast and covered with soil but followed with hydromulch of wood fiber at 2,000-3,000 lb/acre.	Very effective, combines advantages of seed coverage and mulching.	2-3	6-8	680-865
All of the above treatments offer only minimal protection from impact of raindrops and water flowing over the surface, but all are weed free.				
5. Straw or hay broadcast with straw blower on the surface at 3,000 lb/acre and tacked down (asphalt emul-sion, Terratack II, etc.). Seed and fertilizer broadcast with hydroseeder or by hand.	Common elsewhere in U. S. Very effective as energy absorber, mulch; and straw forms small dams to hold some soil. May be weedy depending on straw source. Not for cut slopes steeper than 2:1. Cost would increase significantly if slopes over 50 feet from access, or application is uphill.	5-7	8-10	650
6. Straw broadcast 4,000 lb/acre rolled to in-corporate (punched) another 4,000 lb straw broadcast and rolled, seeded and fertilized. Seed and fertilizer broadcast with hydro-seeder or by hand.	Common difficult fill slopes in California very effective. Not possible on most cut slopes. Very weedy. Cost would increase significantly if slopes over 50 feet from access.	6-8	8-10	877-1070
7. Roll-out mats (jute, excelsior, etc.). Held in place with wire staples. Seed and fertilize as in No. 1.	Some are a good mulch, weed free, adapted to small areas. Can be installed any season, cuts or fills. Unsightly. Diffi-cult to install on rocky soils.	5-7	5-10	2400-2700
8. Seed and fertilizer broadcast, or hydro-mulched with fiber (treatment), followed by erosion control chemical such as poly-vinyl acetate at 6:1 dilution (6 parts water) at 1,000 lb solid/acre (approx. 200 gal. PVA).	Very expensive, but will hold soils and seed in some very difficult conditions. May restrict penetration of water into soil. Will not cure below 55°F. Not effective on soils which crack. Will not cure below 55°F. Not effective on soils which crack. Will not support animal or vehicle traffic.	10+	?	1070-1370

[a]1 = minimal, 10 = excellent.

[b]Assumes seed plus fertilizer $150.00, fiber $150/ton, Ecology Control $1.25/lb., PVA $3.00/gal, 1,500 gal hydroseeder with 2 man crew $55.00/hr, labor $13/hr, straw $50/T, straw mulcher with 4 man crew $64/hr (applies 2 T/hr) and markup of 30% for overhead (including equipment depreciation), and profit.

hydroseeding/hydromulching practices are as follows (U. S. Department of Agriculture, Forest Service, 1979; Bradshaw and Chadwick, 1980; Kay, 1976 and 1978):

- Often an expensive and unreliable technique
- Hydromulches may improve germination but do not improve stand density compared to drilling followed by mulching
- Additional nitrogen may be needed to compensate for the wide carbon: nitrogen ratio of the chosen mulch material
- Success or failure of hydroseeding may depend on getting a good legume stand; the presence of nitrogen-fixing legumes is a must for long-term low-maintenance vegetative covers.
- Hydroseeding and hydromulching should be used in special situations such as areas that are too inaccessible or steep for conventional seed drills and other equipment and in those areas where the seed can be kept moist for two to three weeks after seeding.
- Increased rates of application of water, seed, wood fiber, and chemical tack/binder may lead to prohibitively high costs of erosion control for soil covers on waste sites in arid and semiarid regions.
- Direct-seeded shrubs and herbaceous plants often do not withstand the competition from grasses used in the seeding mixture for erosion control during the initial stabilization phase.
- Some wood fiber and paper hydromulches may require measures to remove boric acid, borate, and other potential soil sterilants (U. S. Department of Agriculture, Forest Service, 1979; Bradshaw and Chadwick, 1980; Kay, 1978).

On extremely acid cover soils the order of 4 to 5 tons per acre of lime material is required; about half of this amount can be applied at one time in the hydroseeder, making it necessary to spread the additional lime separately (Bradshaw and Chadwick, 1980).

The capacity ranges for hydraulic seeding/mulching machines are between 150 and 1500 gal. Volumes of water required per acre also range from 150 to 1500 gal. The amount of wood fiber required per acre may range from 500 to 3000 lb. Recently, Kay (1978) has reported that the effectiveness of wood-fiber mulch in controlling erosion and enhancing plant establishment was doubled when the wood-fiber application rate was 3000 lb/acre, compared to conditions where the seed and fertilizer were broadcast and then covered with soil in the absence of wood-fiber mulch. The approximate cost of the latter treatment was $320 per acre, while the addition of the wood from hydromulch treatment raised the cost to $865 per acre (see Table 4-36). However, it was shown that the pregermination erosion control effectiveness was increased threefold by use of wood-fiber mulch.

4.9.4.6 Chemical Mulches and Stabilizers

Some treatments include the use of short-term erosion-control chemical binders and tacks in combination with conventional mulches and water-dispersible mulches (Kay, 1976). Current information on the cost-effectiveness of chemical tacks and binders under a wide range of environmental settings is limited. General information on chemical binders and tacks is given in Tables 4-37 and 4-38.

Chemical mulches should be used alone only when there is no other mulching material, when they are used in conjunction with temporary seeding during periods when mulch is not required, or where waste-site covering operations occur when seeding cannot be done (Clar et al., 1981). At other times chemical tacks and binders may be used on any exposed area which is being stabilized, within permissible limits. The chemical binders may be used in arid regions and on droughty soils, but their effectiveness in lowering soil-moisture evaporation rates is less than that for conventional organic mulches. Chemical binders are, however, excellent for short-term binding/tacking of conventional organic mulches. All chemical binder applications must be inspected, and reapplied if necessary, periodically up to 60 to 90 days or until the plantings have become firmly established. This is particularly necessary after rainstorms that may have dislodged the chemical mulch (Clar et al., 1981).

Chemical soil stabilizers are designed to coat and penetrate the soil surface and bind the soil particles together. They are used to protect bare soil slopes, not subject to traffic, from wind and water erosion during temporary establishment of a seedbed. Chemical stabilizers are used in lieu of and in conjunction with temporary mulch material to provide mulch tack and soil binder. Chemical stabilizers can be applied only to a very finely prepared seedbed. Soil moisture, temperature, and texture influence the success of the application. Their limited applicability and high cost makes them undesirable except where absolutely necessary. It is recommended that chemical soil stabilizers be tested on small, representative plots of ground before deciding to use them extensively. As a general rule, chemical stabilizers do not provide protection for as long a period of time as straw, hay, and other organic mulches.

4.9.4.7 Nonbiodegradable Mulches

Mulches made of nonbiodegradable material, such as fiberglass and various plastics, protect seedbeds during the critical germination and early plant development period, and act as reinforcement following establishment of the vegetative cover. These materials include nettings and loose, stringy products that can become securely enmeshed in the vegetation at the ground surface and in the rootmat. Also see "erosion-control fabrics" in the next paragraph. Proper installation by experienced personnel is vital to the success of these measures. Light applications of crushed stone or gravel can also serve as a long-term mulch. Table 4-39 contains information on specific long-term mulches.

TABLE 4-37

SUMMARY OF CHEMICAL BINDERS AND TACKS
(U. S. Environmental Protection Agency, October 1976)

Use						
Name	Temporary Soil Stabilizer	Mulch	Mulch Tack	Description	Application Method	Manufacturer or Product Information
Aerospray® 52 Binder	X	X		Water dispersible, alkyd emulsion. Nontoxic. Nonphytotoxic. pH 5-6	Any manure containing equipment (as for liquid fertilizer, asphalt emulsions, and water).	American Cyanamid Company Industrial Chemicals and Plastics Division Wayne, New Jersey 07470
Aerospray® 70 Binder	X	X	X	Water dispersible, liquid polyvinyl acetate emulsion.	Hydroseeder. Seed, fertilizer, and wood fiber may be applied with product.	American Cyanamid Company Industrial Chemicals and Plastics Division Wayne, New Jersey 07470
Aerospray® 72 Binder	X	X	X	Water dispersible, liquid alkyd emulsion resin.	Hydroseeder. Seed, fertilizer, and wood fiber may be applied with product.	American Cyanamid Company Industrial Chemicals and Plastics Division Wayne, New Jersey 07470
Aquatack	X	X		Water dispersible. Nontoxic. Nonflammable.	Hydroseeder or any manure containing equipment. Seed and fertilizer may be applied with product.	The Lawton Corporation 1424 South Allec Avenue Anaheim, California 92805
Curasol® AF	X	X	X	Water dispersible, polyvinyl acetate copolymer emulsion. Nontoxic. Nonphytotoxic. pH 4-5	Hydroseeder or any manure containing equipment.	American Cyanamid Corporation 1061 Route 202-206 North Bridgewater, New Jersey 08807
Curasol® AE	X		X	Water dispersible, high polymer synthetic resin. Nontoxic. Nonphytotoxic. pH 4-5.	Hydroseeder or any manure containing equipment. Seed and fertilizer may be applied with product.	American Cyanamid Corporation 1061 Route 202-206 North Bridgewater, New Jersey 08807
DCA-70	X	X	X	Water dispersible, polyvinyl acetate emulsion. Nontoxic. Nonphytotoxic. Nonflammable. pH 4-6.	Hydroseeder or any manure containing equipment.	Union Carbide Corporation Chemicals and Plastics 270 Park Avenue New York, New York 10017
Gunapac 100	X			Water dispersible, modified liquid acrylic resin.	Hydroseeder. Seed, fertilizer, and wood fiber may be applied with product.	The Delta Company Charleston, West Virginia
Liquid Asphalt			X	Asphalt cement that is dispersed or suspended in water or various solvents.	Hand-spray nozzle or an offset distributor bar attached to an asphalt distributor truck.	Asphalt Institute Asphalt Institute Building University of Maryland College Park, Maryland 20740
M-145	X			Water dispersible, liquid resin polymer.	Hydroseeder. Seed and fertilizer may be applied with product.	The Dow Chemical Company Midland, Michigan 48640
Petromat® AB	X	X	X	Water dispersible oil emulsion. Nontoxic. Nonflammable. pH 6.0±0.5.	Any spraying equipment.	Phillips Petroleum Company Chemical Department Commercial Development Division Bartlesville, Oklahoma 74003
Terra Tack	X	X	X	Water dispersible, powdered vegetable gum.	Hydroseeder or, for dry application, standard hopper spreaders (as for fertilizers or lime).	Grace Growers, Inc. P. O. Box 504 Plainfield, New Jersey 07061
Urea-Formaldehyde Foam		X		Urea-formaldehyde resin plus a foaming agent, mixed and foamed with compressed air, then applied to soil. Wetting agent is then applied to the foam. Seed and fertilizer sprayed on top.	Manure containing equipment for resin and foam. Hydroseeder for seed and fertilizer.	U. F. Chemical Company 37-20 30th Street Woodside, New York 11377
XB-2306	X			Water dispersible, liquid reactive polymer.	Injected into slurry at the nozzle of a hydroseeder.	3M Company Adhesives, Coatings and Sealers Division, 3M Center Saint Paul, Minnesota 55101

TABLE 4-38

APPLICATION RATES FOR SELECTED BINDERS AND TACKS
(Clar et al., 1981)

Name	Rate
Aerospray 52 Binder	1 - Steeply inclined, exposed slopes - 1 gal/100 ft^2 - concentrated 2 - Seedbed - 30-45 gal (concentrate) per acre in dilution ratios varying up to 10 parts water to 1 part chemical.
Aerospray 70 Binder	On steeply inclined, exposed slopes - 0.5 to 1.5 gal/yd^2 of mixture. Mixture can have ratios ranging from 7 to 20 parts water.
Aerospray 72 Binder	
Aquatain	Mixture - 5.5 parts water to 1 part aquatain. Approximately 3 gallons aquatain, plus required water, per 1000 square feet of surface area is normally required for most soil surfaces.
Curasol AE	Flat Areas - 30 gallons to 1000 gallons water for moist soils, 2000 gal - dry soils. 3:1 - 2:1 Slopes - 40-55 gallons to 1000 gallons water for moist soils, 2000 gal - dry soils. 1.5:1 Slopes - 55-65 gallons to 1000 gallons water for moist soils, 2000 gal - dry soils. Swales and Ditches - 90-100 gallons to 1000 gallons water for moist soils, 2000 gal - dry soils.
Curasol AH	For Straw Mulch Tack - 30-45 gallons to 150 to 300 gallons water with mulch blower, 300-500 gallons water with hydroseeder, per acre. For Hay Mulch Tack - 20-30 gallons to 150-300 gallons water with mulch blower, 300-500 gallons water with hydroseeder, per acre.
DCA-70	Soil Stabilizer - 1:1 ratio with 0.5 or more gallons per square yard. Chemical Mulch - 1 part to 20 parts water, 0.5 gallons per square yard - perm. soils. Tack - 1 part to 10-20 parts water, disperse 330-950 gallons of solution per acre depending on strength, each acre should have 30-45 gallons of concentrate.
Liquid Asphalt	Mulch - Spray rate - 0.15 - 0.30 gallons per square yard Tack - Spray rate - 0.1 gallon per square yard Spray rate emulsified - 0.04 gallons per square yard
M-145	On Steeply Inclined, Exposed Slopes - 1.5 to 2.0 gal/yd^2 of mixture. Mixture usually ranges from 5 to 10 parts water for every part chemical.
Petroset SB	Highly Variable - depends on different soil textures, desired penetrations, and intended usages. In general, the greater the dilution ratio, the deeper the penetration and the weaker the binding strength for a given soil condition. Specific applications and cot formulas and nomographs are furnished by the manufacturer.
Terra Tack	Stabilizer - wet - 50 lbs in 2000 gallons water with seed per acre. Dry - 86 lbs per acre with seed Mulch Tack - long fiber mulches - 1:20 mix ratio - apply 1000 gal per acre. Short fiber mulches - 1:40 mix ratio - apply 2000 gal per acre.

TABLE 4-39

GUIDE TO LONG-TERM NONBIODEGRADABLE MULCHES[a]

Mulch Materials	Application Rates	Remarks
Crushed stone (including limestone)	6 to 10" thick	Most durable (especially granite), use on cover soils prone to slipping, frost heaving, and seepage
		Limestone on acid areas will not last as long as other materials
Gravel	6 to 10" thick	Use on gentle slopes and flat areas only, seepage of water, and frost heaving
Slag	4 to 6" thick	By-product of steel blast furnace, uses similar to crushed stone and gravel
		Do not use with certain filter fabric (Filter-x, etc.)
Fiberglass	Blanket should completely cover the disturbed area	Use without additional mulch
	Strands applied at a rate of 850 to 1,100 lb/acre	Use only on limited critical areas because of cost
		Applied as a mat or blanket or in long strands
		Blanket form should be stapled
		Long strands applied by compressed air spraying
		Erosion from beneath may be a problem with blanket
Enkamat, Geofab and related synthetic fabrics	Use available sheet widths and controlled size openings. Place a 3-in. layer of sand having wide gradation of particle sizes on top of fabric prior to use of riprap	Fabrics must be placed in intimate contact with underlying soil. On fill sites, compact the soil to 90% of the standard Proctor density before placing the fabric.
Riprap	Use when overland flow rate of water exceeds 10 ft/sec	Riprap is placed on top of the underlying layer of sand which covers the synthetic fabric. The exact sand layer thickness has not been determined, but it must be placed between the fabric and the riprap.

[a]From Nolan et al., 1976 and 1978; cited in Lee et al., 1984.

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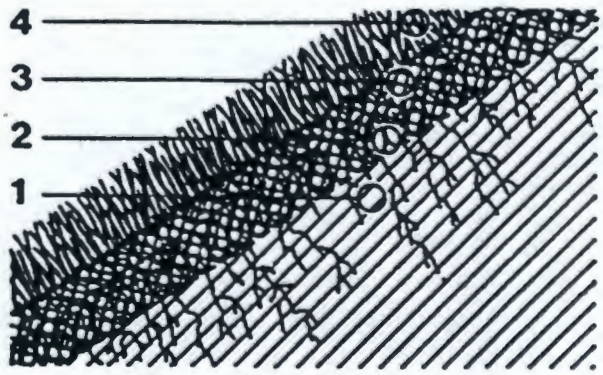
4.9.4.8 Erosion-Control Fabrics

Erosion-control fabrics consist of synthetic fabric matting that can be used as a replacement for concrete, asphalt, and rock riprap. See also the discussion of "geotextiles" in section 3.4.3.6. Erosion-control fabrics allow the establishment and maintenance of vegetation where nonvegetative stabilization alone would be aesthetically unpleasing. Seed is sown intc the material and grass grows through it and eventually covers it. See Figure 4-38 and also detail drawings in Appendix B, "Case Histories." Soil and sediment particles are held by the filaments of the mat. Installation and maintenance of these materials can be less expensive than the use of conventional materials.

FIGURE 4-38

"ENKAMAT" INSTALLED ON SLOPES



1 = Subsoil
2 = Enkamat
3 = Sedimentation
4 = Grass Area

Claims have been made that these mats are effective on slopes up to 1:1 over a wide range of soil conditions; have successfully withstood 14 in. of rain during the first month after installation; and have stabilized both natural and artificially compacted soils. Manufacturers say these materials are thoroughly compatible with all grass varieties and other types of vegetation. "Enkamat" is the trade name of one soil reinforcement material (Figure 4-38). In sandy soils, an underlay of filter fabric should be used.

Current thinking holds that fabric mats are especially useful on limited and highly critical areas because of high installation costs. These areas include steep slopes and areas of high wind velocities. Disadvantages other than expense include (U. S. Department of Agriculture, Forest Service, 1979):

- High labor costs for pinning and anchoring the fabrics
- Erosion from beneath
- General ineffectiveness on rocky areas and rough surfaces

Polyester fabric mats (nonwoven) should be installed in accordance with the manufacturer's specifications. Staples or ground fasteners may consist of plain iron wire (No. 8-11 gauge); broad wire U-staple; narrow wire V-staple; T-staple; and narrow, triangular wood survey stakes. Stake lengths may range from 12 to 18 in. depending on the expected load maxima. Staples should be placed down the mat centers at 3-ft intervals. Prior to installation of the fabric mats one must:

- Shape and grade the slope, or other area to be protected, as required
- Remove all rocks, clods, or debris larger than 2 in. in diameter that will prevent contact between the net and the soil surface
- When open-weave nets are used, lime, fertilizer, and seed may be applied either before or after laying the net. When nonwoven matting is used, apply the soil amendments and seed before the matting is laid (Clar et al., 1981). Traffic patterns should be across the slope to minimize the initiation of rills.

4.9.4.9 Vegetative Maintenance

Proper management and maintenance of the vegetative cover at a waste site are vital to maintaining its stability. There are essentially two management strategies that can be employed at a successfully covered waste site. The more costly management strategy is the conventional maintenance practice (Lutton, Regan, and Jones, 1979).

Once the selected vegetation is established on the landfill, at least a minimum amount of maintenance is necessary to keep less desirable, native species from taking over any weak areas in the cover. In most areas judicious, occasional mowing will keep down weed and brush species. Mowing should not be done indiscriminately, however. The blades of mowing machines may cut into local high spots, leaving them devoid of vegetation (Heim and Machalinski, 1980), and the tires of mowing tractors may cause ruts to form. Traffic patterns should be varied to avoid this. Annual fertilization (and liming if necessary) will generally allow desirable species to out-compete the lower-quality weedy species. Occasional use of selective herbicides usually controls noxious invaders, but care must be taken to avoid injuring or weakening the desirable species, lest more harm than benefit result in the long run. In rare circumstances, large insect populations may threaten the stand of vegetation so that insecticide application becomes desirable.

The other management strategy strives for a self-sustaining vegetative cover consisting of grass-legume mixtures with periodic lime, phosphorus and potassium fertilizer applications as necessary to maintain a minimum vegetative cover to control erosion. Under this management strategy, natural plant succession will proceed and invasion of the site by shrubs and trees may occur. Control measures to limit the establishment and growth of deep-rooted shrubs and trees should be implemented, if required. Mowing twice a year or the use of herbicides to kill undesirable shrub and tree species should be considered.

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Grazing is a possible alternative to mowing. Tests can be performed on the grasses to insure that they are free of toxic substances. Grazing combines the benefits of keeping the grasses short, returning nutrients to the soil through animal wastes, and putting the land to economic use. Should tests reveal contamination of the grass, of course, grazing should be immediately terminated.

A refertilization and reliming program may have to be established to ensure that the site receives sufficient nutrients to sustain the established vegetation, particularly for domestic grasses and legumes. In general, the fertilizer requirements of native species would be lower than that for domestic grasses and forbs.

The most common methods used to determine refertilization/reliming needs are soil tests, tissue tests, and observing deficiency symptoms. Soil tests are an important method for identifying nutrient deficiencies, with the exception of nitrogen, which is best detected by onsite observations or tissue tests. When using soil analysis for lime and fertilizer requirements, rely on qualified suggestions of State soil testing labs or commercial labs; and follow recommended procedures for soil sampling (U. S. Department of Agriculture, Forest Service, 1979).

Weeds may have to be removed from a cover system for a variety of reasons. They may present a fire hazard, especially along roads; they may be aesthetically displeasing; they may be noxious, or provide too much competition with desired plants. Both mechanical and chemical means can be employed. In general, chemical means should be used only in highly selective situations such as for control of noxious weeds (U. S. Department of Agriculture, Forest Service, 1979).

The use of insecticides may need to be considered. Before making any attempt to control insects, you should know (1) the name of the insect you want to control; (2) the dangers of using chemicals to control insects; and (3) whether the harm caused by the insects is sufficient to warrant use of an insecticide (U. S. Department of Agriculture, Forest Service, 1979).

4.9.5 Nonvegetative Measures

4.9.5.1 Stone Stabilization

Heavy applications of crushed stone, gravel, or slag can be used to stabilize highly toxic surfaces, or excessively wet seepage areas on slopes. Crushed stone or gravel mulches retain their effectiveness indefinitely if properly applied and protected from compacting traffic. Sediment reduction is estimated at 70 to 90 percent, and nutrient runoff reduction at 50 to 70 percent. Stones 0.5 in. or greater in diameter will protect against rain splash and sheet flow and can withstand wind velocities up to 85 mph (U. S. Department of Defense, no date).

In certain areas of dry climate and abundant gravel, for example the Sacramento Valley of California, it may be feasible to construct the entire surface layer of gravel. Such a surface would be highly erosion-resistant. It would be highly pervious, but so long as the barrier and drainage layers of the cover system (discussed previously) were properly designed and built, the system should function effectively. The site would be less aesthetically pleasing than a vegetated site, but it would be relatively maintenance-free.

4.9.5.2 Soil-Cement

Soil-cement has been discussed in Chapter 3 under nonsoil materials usable in cover systems, and its use is discussed in detail below in sections dealing with barrier and foundation layers. It may be mentioned here that the surface layer could be constructed of soil-cement. Soil-cement is a relatively impervious, rigid material, and the same cautions stated elsewhere in this Handbook as to the risk of cracking would apply. A soil-cement surface layer would be relatively maintenance-free except for repairing cracks. These should be

TABLE 4-40

MAINTENANCE PRACTICES FOR SURFACE STABILIZATION MEASURES[a]

Practice	Maintenance Procedures
Conventional mulches (biodegradable)	Inspect periodically Remulch bare spots during design life
Chemical stabilizers/tacks	Inspect periodically Reapply to bare spots during design life
Nonbiodegradable mulches and fabrics	Inspect periodically Reapply where necessary Fiberglass and plastic mats should be checked for erosion underneath the blanket
Stone surfacing	Inspect periodically Reapply where necessary
Soil reinforcement materials and erosion control fabrics	Inspect after each storm until vegetation has been established and look for undercutting of material Periodic inspection after vegetation has been established
Channel stabilization	Periodic inspection and repair according to SCS standards and specifications for each practice

[a]From Lee et al., 1984

anticipated, however, and a regular inspection program should be followed. Soil-cement will not support vegetation, and a soil-cement surface could be aesthetically inferior to a vegetated surface. Also, small cracks in a soil-cement surface would tend to be rapidly colonized by clumpy vegetation, which would have to be killed by herbicides before it extended its roots and disrupted the cover layer.

4.9.6 Maintenance of Stabilization Measures

Proper maintenance of any stabilization practice is essential for its continued effectiveness. Table 4-40 lists maintenance practices for nonvegetative measures. Judgment is required in applying various chemical stabilizers and fabric mats because their high cost dictates that their use be limited to small areas of critical and sensitive waste sites.

4.10 Surface Water Management

4.10.1 General

Surface-water management refers to all features concerned with the management or control of runoff. Runoff is affected by:

- Surface slope
- Length of slope
- Uniformity of slope
- Drainage pattern
- Type and density of vegetation
- Soil texture
- Erosion resistance of soil
- Engineered ditches, diversions, and structures

Two obvious factors affecting the rate and amount of runoff are the surface's slope and the length of uninterrupted slope. As the slope angle increases, so does the potential velocity of runoff. The point where the soil begins to erode is generally a function of the type of soil and the type and density of vegetation. Also, as the length of slope (per given width of slope) is increased, the larger the area receiving precipitation becomes. This larger area has the effect of increasing the amount of runoff to be handled, as well as increasing the contact time between the runoff and the cover's surface.

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Another factor having a direct impact upon runoff is the uniformity of the slope. Naturally occurring discontinuities in a site's surface such as gullies, hollows, dips, and cracks generally will slow down the rate of runoff and can cause runoff to collect and pond. The latter effect is of concern as it forms wet spots, which are prime sources of infiltrating water. Generally a good preconstruction practice is to grade the site to a uniform slope.

Other factors that must be considered in the site's surface-water-management plan are the site's drainage patterns (natural and engineered), the type and density of vegetation at the site, and texture and erosion resistance of the soil at the surface. Each of these factors has an influence on the balance between infiltration and runoff.

The designer must first consider the extent to which natural topography and surface conditions can be utilized. As a rule, it is desirable to avoid extreme grade modifications wherever possible. Therefore, the designer should make changes in the existing topography only with care; however, the designer must recognize existing or potential problems. These problems include severe erosion of the surface soil due to too steep a slope, surface cracks which allow runoff to enter the subsoil or aid in creating gullies and rills, and conditions which would lead to the destabilization of collapsible soils (such as loess) or soils susceptible to piping (dispersive soils).

4.10.2 Surface Water Management Program (SWMP)

Runoff as a component of the water balance was discussed in section 4.2. The goal of the SWMP is to handle the runoff in a controlled fashion; that is, to conduct it off the site in such a way that it does not erode the cover system.

Four good sources of information for SWMP design, from which much of the material here was drawn, are:

a. Lee et al. (1984), "Restoration of Problem Soil Materials at Corps of Engineers Construction Sites."

b. Lutton, Regan, and Jones (1979), "Design and Construction of Covers for Solid Waste Landfills."

c. JRB Associates, Inc. (1982), "Handbook for Remedial Actions at Waste Disposal Sites."

d. Chow (1959), "Open Channel Hydraulics."

In addition, the cover designer will fund abundant information on riprap channel linings in Anderson, Paintal, and Davenport (1970), and extensive research data on erosion resistance of grass-lined channels in Ree and Palmer (1949).

It should be clearly understood that the SWMP is critical and unique in one respect. Together with the vegetative layer, it is the only part of the

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cover system that is directly affected by emergency weather conditions (violent storms). As explained in section 4.2, the possible infiltration rate into any soil has a maximum value, and subsurface flows higher than this are impossible. On the other hand, there is no precise limit to the amounts of water that the SWMP may sometimes be called upon to handle. For this reason the designer should exercise the utmost diligence to insure that both the capacity and the durability of the SWMP are satisfactory to meet their expected demands.

Elements of the SWMP will generally fall into the following categories:

- Land grading
- Waterways
- Diversion structures
- Check dams
- Outlet structures

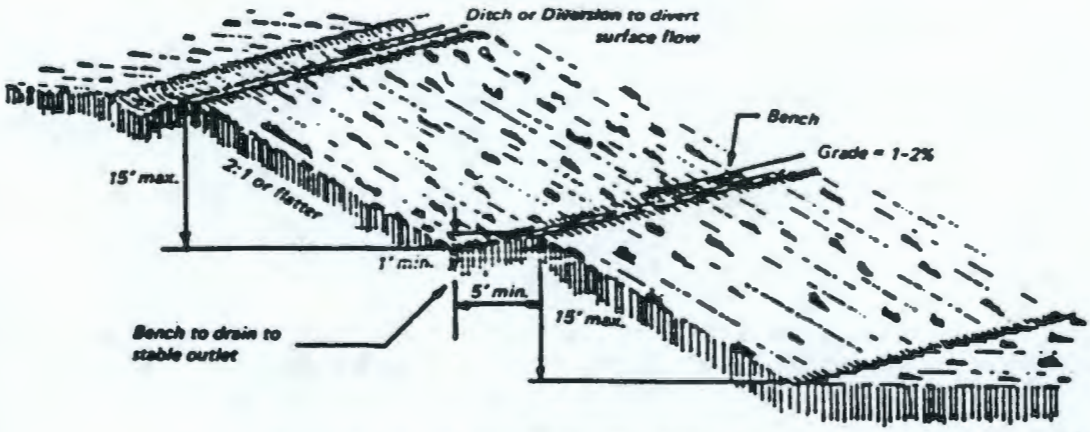
Examples of SWMP elements may be found in the Case Histories in Appendix B.

4.10.2.1 Land Grading

Land grading is the reshaping of a site's existing topography in order to maximize nonerosive runoff and promote the establishment of vegetation. Generally, land grading involves cut-and-fill operations to establish the site's preoperational or closure topography. Reverse-slope benches (Figure 4-39) are also utilized to help stabilize and protect slopes and disturbed areas.

FIGURE 4-39

SLOPE WITH REVERSE-SLOPE BENCH



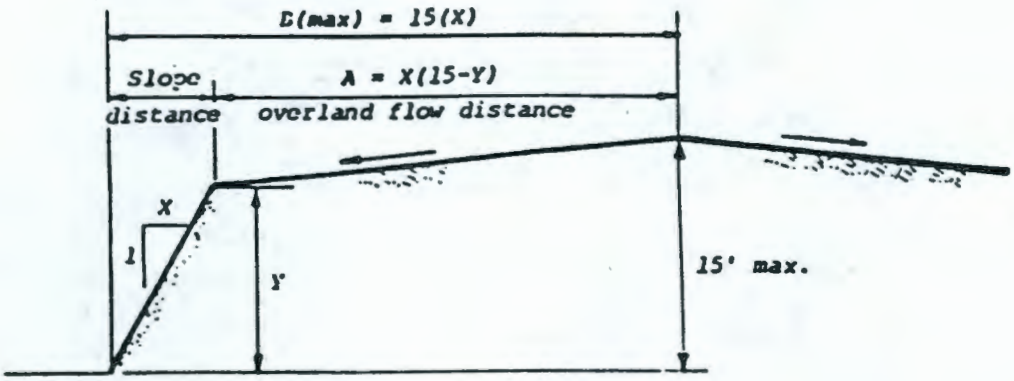
(U. S. Department of Agriculture, Soil Conservation Service, 1975)

This grading or "contouring" is carried out in accordance with a plan based on an engineering survey and layout. This plan is based on topographic surveys and soil investigations which outline the parameters within which the contouring operation must operate. These investigations should outline conditions relating to slope stability, drainage patterns, the SWMP's effect on adjacent property, and requirements for drainage and water removal.

Maximum overland flow distances should be controlled as shown in Figure 4-40. Land-grading design criteria and considerations are presented in Table 4-41. Table 4-42 outlines items that bear consideration when preparing construction specifications for land-grading. Serrated cut slopes should be constructed in accordance with Figure 4-41.

FIGURE 4-40

MAXIMUM ALLOWABLE OVERLAND FLOW DISTANCE



The maximum total horizontal overland-flow-plus-slope distance (B) should not exceed 15 times the side slope (X) of the cut or fill slope. Maximum allowable overland flow* distance (in feet) to the top of the slope with no diversion of surface water is determined by use of the formula A = X(15-Y),

where:

A = Maximum overland flow distance in feet to slope crest.
B = Maximum horizontal distance in feet (not to exceed 15X).
X = Side slope; horizontal distance in feet to 1 foot vertical
Y = Vertical interval; height of cut/fill slope in feet measured vertically from bottom elevation of slope to slope crest.

*If maximum allowable overland flow is exceeded, surface water should be diverted from the slope face and carried to a stable outlet, or conveyed downslope with a designed structure.

(U. S. Department of Agriculture, 1975)

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TABLE 4-41

LAND GRADING DESIGN CRITERIA AND CONSIDERATIONS

a. Provisions (such as waterways, diversions, and outlet structures) should be made to conduct surface runoff safely to storm drains, protected outlets, or stable water courses to insure that surface runoff will not damage slopes or other graded areas.

b. Cut and fill slopes should not be steeper than 2:1. Where the slope is to be mowed, the slope should not be steeper than 3:1 (4:1 is preferred because of safety factors related to mowing steep slopes).

c. Reverse-slope benches or diversions should be provided whenever the vertical interval (height) of any 2:1 through 5:1 slope exceeds 15 ft (Figure 4-39).

d. The following applies to reverse-slope benches (Figure 4-39).

   1. Benches should be located so as to divide the slope face as equally as possible and should convey the water to a stable outlet. Soils, seeps, rock outcrops, etc., should also be taken into consideration when designing benches.

   2. Benches should be wide enough to accommodate the construction equipment in use and provide for ease of maintenance.

   3. Benches should be designed with a reverse slope of 5:1 or flatter to the toe of the upper slope and with a minimum of 1 ft in depth. Bench gradient to the outlet should be between 1 and 2 percent.

   4. The flow length within a bench should not exceed 800 ft unless accompanied by appropriate design and computations.

e. Surface water should be diverted from the face of all cut and/or fill slopes by the use of diversions, ditches, and swales or conveyed downslope by the use of a designed structure, except where:

   1. The length of overland flow (in feet) to the crest of the slope (Figure 4-40) does not exceed the distance "A" for any combination of side slopes and vertical intervals.

   2. The face of the slope is stabilized and the face of all graded slopes is protected from surface runoff until they are stabilized.

   3. The face of the slope is not subjected to any concentrated flows of surface water from natural drainageways, graded swales, downspouts, etc.

f. Serrated cut slopes should be constructed so as to facilitate long-lasting vegetative stabilization. These serrations should be made in rippable rock with conventional equipment as the excavation is made. Each step or serrate shall be constructed on the contour and will have steps cut at nominal 2-ft intervals with nominal 3-ft horizontal shelves. These steps will vary depending on the slope ratio of the cut slope. The normal slope line is 1.5H:1V. These steps will weather and act to hold moisture, lime and fertilizer, and seed, and to produce a much quicker and longer lived vegetative cover and slope stabilization. Overland flow is diverted from the top of all serrated cut slopes and is carried to a suitable outlet (Figure 4-41).

g. Slopes should not be created so close to property lines as to endanger adjoining properties without adequately protecting such properties against erosion, slippage, settlement, subsidence, or other related damages.

TABLE 4-42

GUIDANCE FOR GRADING CONSTRUCTION SPECIFICATIONS

1. All graded or disturbed areas including slopes should be protected during clearing and construction in accordance with the approved sediment control plan until they are permanently stabilized.

2. All sediment control practices and measures should be constructed, applied, and maintained in accordance with the approved sediment control plan.

3. Topsoil required for the establishment of vegetation should be stockpiled in amount necessary to complete finished grading of all exposed areas.

4. Areas to be filled should be cleared, grubbed, and stripped of topsoil to remove trees, vegetation, roots, or other objectionable material.

5. Areas where topsoil is to be placed should be scarified to a minimum depth of 3 in. prior to placement of topsoil.

6. All fills should be compacted as required to reduce erosion, slippage, settlement, subsidence, or other related problems.

7. All fill should be placed and compacted in layers. Loose lift thickness should not exceed 8 in. in thickness (may vary with size of compactor).

8. Fill material should be free of brush, rubbish, rocks, logs, stumps, building debris, and other objectionable material that would interfere with or prevent construction of satisfactory fills.

9. Frozen materials or soft, mucky, or highly compressible materials should not be incorporated into fills.

10. Fill should not be placed on a frozen foundation.

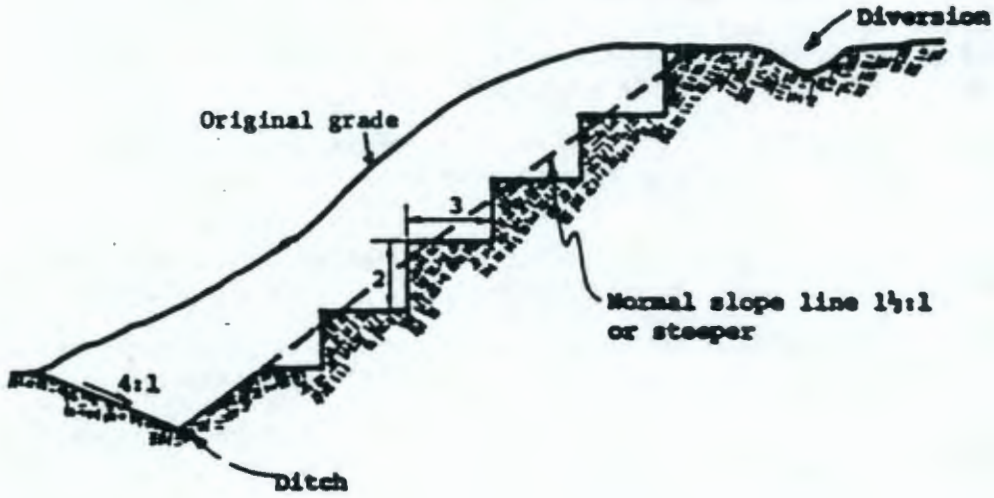
11. All benches should be kept free of sediment during all phases of development.

12. All graded areas should be permanently stabilized immediately following finished grading.

13. Stockpiles, borrow areas, and spoil areas should be shown on the plans.

FIGURE 4-41

TYPICAL SECTION OF SERRATED CUT SLOPE



4.10.2.2 Waterways

A waterway has been defined as "a permanent, design stormwater conveyance channel, shaped and lined with appropriate vegetation or structural material to safely convey excess stormwater runoff" (Lee et al., 1984). However, an uncontrolled hazardous waste site's SWMP may call for temporary waterways, in order to stabilize the site, which may not be included in the final closure plan. The discussion below applies, as appropriate, to such temporary waterways, as well as to the more formally defined permanent ones.

Note, also, that wherever two planar sloping surfaces meet in a dihedral angle, a "swale" is formed, which will become a de-facto waterway under stormwater conditions.

The design of a waterway requires consideration of the following factors:

- Total stormwater capacity requirements
- Velocity of flow
- Channel cross section
- Land availability
- Channel lining

- Maintenance requirements
- Vertical and horizontal channel alignment
- Compatibility with the site's SWMP and surrounding environment
- Outlet conditions
- Cost

The commonly accepted design capacity for waterways has been the peak flow from a 10-year-frequency storm. However, some state and local drainage criteria require a design based on higher stormwater requirements than the 10-year-frequency storm. Therefore, as appropriate, state and local agencies should be consulted when determining capacity requirements. The rainfall intensity can be estimated from site-specific documentation, if available, or if need be, from rainfall-intensity maps which may be found in sources mentioned above in Chapter 2 under "climate."

A number of limits are imposed upon the designer by flow-velocity considerations. The designer is faced with moving a volume of runoff off the site rapidly. From this standpoint, a design which maximizes the velocity of flow would seem to be called for. However, three controlling factors are the erosion threshold of the lining materials, feasibility of constructing the necessary channel slopes, and availability of land for the purpose. If the velocity of flow in a channel will scour the lining, then an adjustment needs to be made in the channel's cross section, slope, or both. Consideration may also be given to decreasing the volume in a given waterway by increasing the total number of channels in the SWMP. However, there may be limitations on how much of the site area is usable for waterways, or space limitations on channel cross sections and slopes.

Channel cross sections can be rectangular, V-shaped, parabolic, trapezoidal, or circular (as with channels formed from corrugated metal pipe). Properties of typical cross sections are shown in Table 4-43. Where conditions call for relatively small flow volumes, vee-shaped, circular, and parabolic channels with small top widths have been used. An example is a roadside ditch. Where velocities in these ditches are relatively low and water infiltrating into the cover soil from the ditch is not a problem, a grass lining is satisfactory. However, where higher velocities are encountered (as in steep slopes), a more erosion-resistant lining such as concrete, soil cement, bituminous material, or riprap is required.

Wide, shallow parabolic channels are used where the volume of water is larger than that for V-shaped channels but the velocities are low. Space

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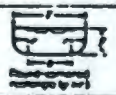
availability is a big factor for this wide, shallow type of channel. Grass is a common lining material, but riprap or riprap/grass combinations can be useful where some dissipation of energy (velocity) is desired.

Trapezoidal and rectangular channels are normally utilized where large volumes of water are to be carried at a relatively high velocity. Usually trapezoidal channels are preferred over rectangular ones, as it is usually easier to maintain the stability of the cut (side stability). Normally, only the more erosion-resistant linings (concrete, asphalt, riprap, etc.) are used in these channels.

Specific procedures for the design of waterways are presented in Appendix H.

TABLE 4-43

TYPICAL CHANNEL CROSS-SECTIONAL CHARACTERISTICS
(Chow, 1959; Courtesy McGraw-Hill Book Co., Inc.)

Section	Area A	Wetted perimeter P	Hydraulic radius R	Top width T	Hydraulic depth D
Rectangle	by	$b+2y$	$\frac{by}{b+2y}$	b	y
Trapezoid	$(b+my)y$	$b+2y\sqrt{1+m^2}$	$\frac{(b+my)y}{b+2y\sqrt{1+m^2}}$	$b+2my$	$\frac{(b+my)y}{b+2my}$
Triangle	my^2	$2y\sqrt{1+m^2}$	$\frac{my}{2\sqrt{1+m^2}}$	$2my$	$\frac{1}{2}y$
Circle	$\frac{1}{8}d^2(\theta-\sin\theta)$	$\frac{1}{2}d\theta$	$\frac{1}{4}\left(1-\frac{\sin\theta}{\theta}\right)d$	$\frac{\sin\frac{1}{2}\theta\, d}{\text{or}\ 2\sqrt{y(d-y)}}$	$\frac{1}{4}\left(\frac{\theta-\sin\theta}{\sin\frac{1}{2}\theta}\right)d$
Parabola	$\frac{2}{3}Ty$	$T+\frac{8}{3}\frac{y^2}{T}$*	$\frac{2T^2y}{3T^2+8y^2}$	$\frac{3}{2}\frac{A}{y}$	$\frac{2}{3}y$
 Semicircle (Flat-bottomed trapezoid by arc)	$\left(\frac{\pi}{2}-2\right)r^2+(b+2r)y$	$(\pi-2)r+b+2y$	$\frac{(\pi/2-2)r^2+(b+2r)y}{(\pi-2)r+b+2y}$	$b+2r$	$\frac{(\pi/2-2)r^2}{b+2r}+y$
Circle-bottomed trapezoid	$\frac{Tr}{2}-\frac{r^2}{2}(1-\cos^{-1}\alpha)$	$\frac{T}{2}\sqrt{1+r^2}-\frac{3r}{2}(1-\cos^{-1}\alpha)$	$\frac{A}{P}$	$[2(r+y)-r]+r\sqrt{1+r^2}$	$\frac{A}{T}$

* Satisfactory approximation for the interval $0 < z \leq 1$, where $z = 4y/T$. When $z > 1$, use the exact expression $P = (T/2)[\sqrt{1+z^2}+(1/z)\ln(z+\sqrt{1+z^2})]$.

4.10.2.3 Diversion Structures

A diversion is a small structure that is used to intercept sheet flow from and to critically disturbed areas and convey or guide this water to stable outlet points. It may be a temporary or a permanent fixture. Berms or dikes, ditches or swales, or combinations of these fall under the classification of diversion structures.

In selecting a diversion structure, consideration should be given to the following factors:

- The amount of runoff to be handled
- The site's topography
- The diversion's finished slope
- Required service life
- Ease of construction and removal (if necessary)

Figures 4-42, 4-43, and 4-44 show diversion swales or ditches, dikes or berms, and ditch-berm combinations, respectively. Table 4-44 gives design criteria, while construction-specification guidance is given in Table 4-45. Table 4-46 gives some examples of maximum velocities for unlined and vegetatively lined swales.

FIGURE 4-42

TYPICAL DIVERSION DITCH OR SWALE
(U.S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

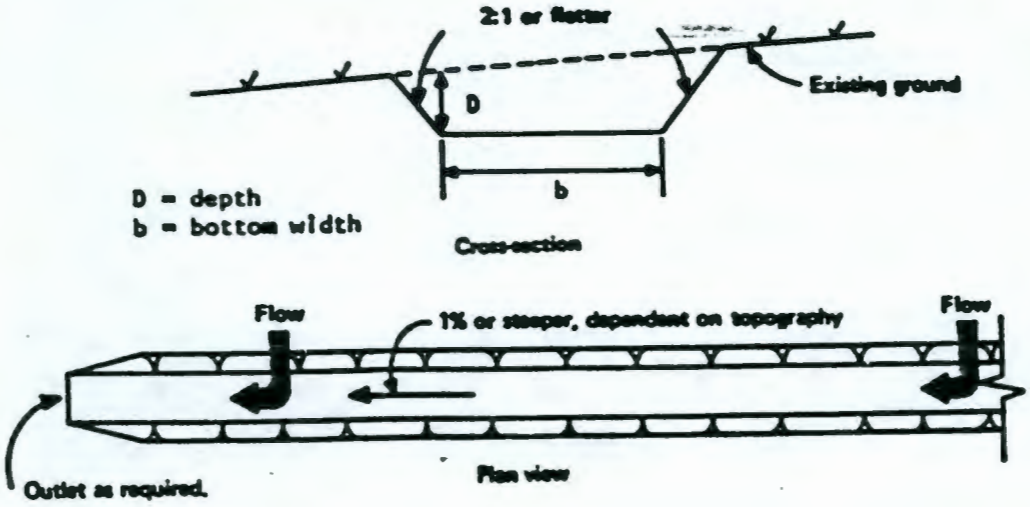


FIGURE 4-43

DIVERSION DIKE OR BERM
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

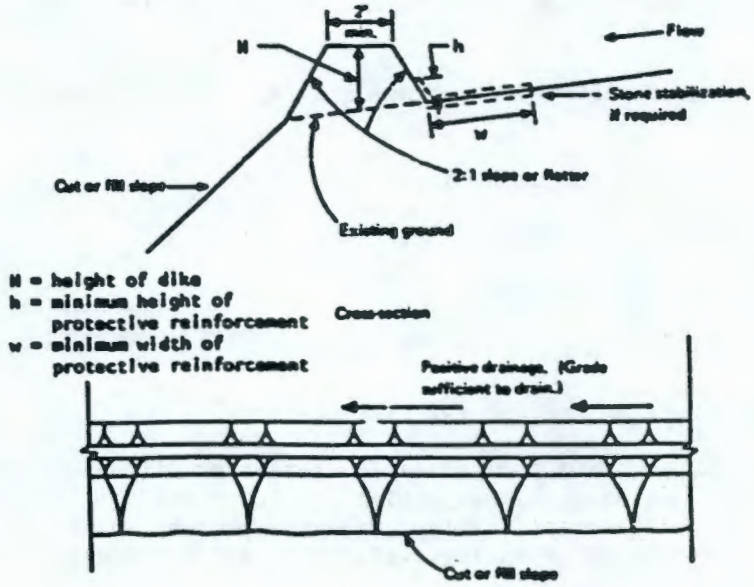
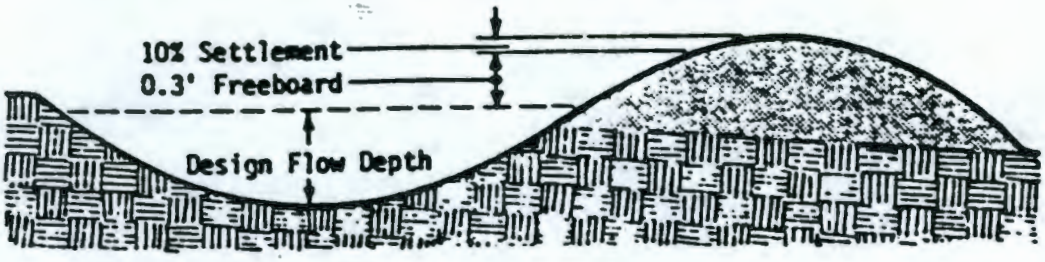
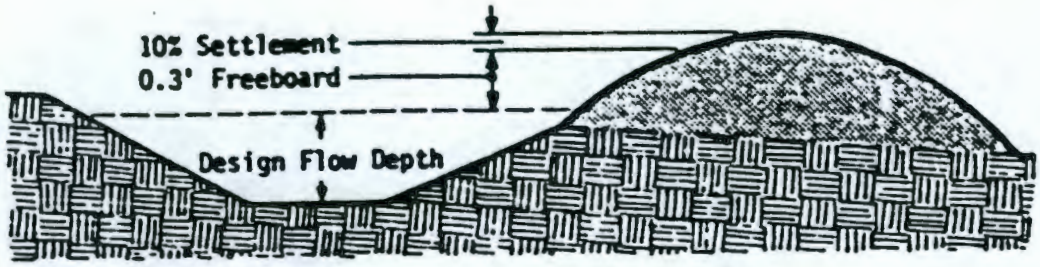


FIGURE 4-44

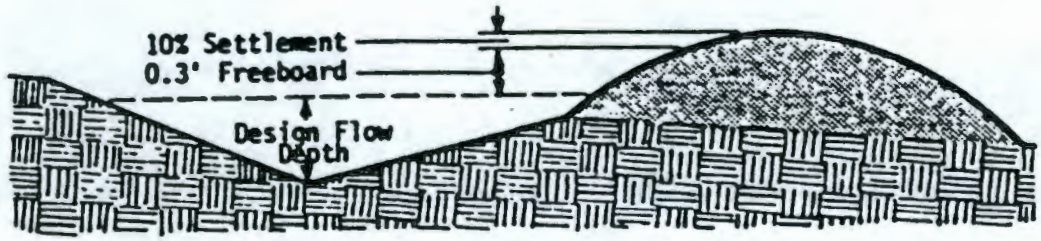
COMBINATION DIVERSION
(VIRGINIA SOIL AND WATER CONSERVATION COMMISSION, 1980)



Typical Parabolic Diversion



Typical Trapezoidal Diversion



Typical Vee-Shaped Diversion

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TABLE 4-44

DESIGN CRITERIA FOR DIVERSION STRUCTURES

a. Primary applications of a diversion structure include (Lee, et al., 1984):

   1. Preventing surface runoff from higher-elevated undisturbed or stabilized areas from coming in contact with exposed soil surfaces (graded spoils, cleared areas, roadways, etc.) and causing erosion.

   2. Shortening the length of graded slopes, thereby protecting lower portions of a hillside or roadway from highly erosive surface water flow.

   3. Preventing sediment-laden runoff from an exposed slope from exiting the construction site without first passing through a sediment detention structure.

b. A dike (Figure 4-43) should be used only as a temporary structure where relatively small amounts of runoff are expected.

c. Diversion structures that will exist for more than 30 days should be stabilized with grass, riprap, etc.

d. Applicable locations for diversions include:

   1. Upgradient of any disturbed area to reduce the volume of surface runoff which will attack the disturbed area.

   2. Along steep or long slopes to control sheet flow and reduce the slope length and steepness factor.

   3. Along the base or toe of denuded and/or disturbed slopes to collect sediment-laden runoff and convey it to a settling basin.

   4. Around soil stockpiles.

   5. Along the sides of access roads.

e. All swales (Figure 4-42) should be designed along the criteria established for channels.

f. All temporary diversions and diversion combinations (Figure 4-44) should be designed to withstand the peak discharge from a 2-year, 24-hour storm.

g. Swale channel velocities should be such that they will not allow an undesirable amount of erosion to take place nor allow excessive sedimentation. See Table 4-46.

TABLE 4-45

CONSTRUCTION SPECIFICATION GUIDANCE FOR DIVERSION STRUCTURES

1. All trees, brush, stumps, obstructions, and other objectionable material should be removed and disposed of so as not to interfere with proper functioning of the diversion structure.

2. Whenever feasible, the dike should be built before any disturbance begins.

3. All dikes should be machine compacted to prevent failure and should be at least 85 percent standard Proctor density. In wooded areas where top-of-slope access is limited, diversion dikes can be constructed as the slope is being finished by moving soil upslope and dumping it at the crest. Compaction is sacrificed in this instance.

4. All diversion dikes should have positive drainage to an outlet.

5. Dike stabilization should begin within 15 days of construction or less as site conditions dictate.

6. The swale should be excavated or shaped to line, grade, and cross section as required to meet the criteria specified herein and be free of bank projections or other irregularities which will impede normal flow.

7. Perimeter swales should have a minimum grade of 1 percent and the bottom should be flat

8. Fills should be compacted as needed to prevent unequal settlement that would cause damage in the completed swale.

9. All earth removed and not needed in construction should be spread or disposed of so that it will not interfere with the functioning of the swale.

10. Diverted runoff from a protected or stabilized upland area should outlet directly onto a stabilized area or into a grade stabilization structure.

11. Diverted runoff from a disturbed or exposed upland area should be conveyed to a sediment trapping device such as a sediment trap or sediment basin or within an area protected by any of these practices.

12. Vegetative stabilization should be accomplished using information from Tables H-2 and H-3 (Appendix H) and 4-46.

13. Periodic inspection and required maintenance should be provided. Diversion structures should be inspected at least every two weeks and repairs made when necessary.

9 3 1 2 9 0 4 1 1 6 4

TABLE 4-46

EXAMPLES OF PERMISSIBLE VELOCITIES FOR STABLE DIVERSIONS
(Lee et al., 1984)

a. Swales not completely lined with vegetation

	Maximum velocity, feet per second	
	Clean water	Water transporting colloidal silt
Sand and sandy loam	1.50	2.5
Silt loam	2.00	3.0
Sandy clay loam	2.00	3.5
Clay loam	3.00	4.0
Clay, fine gravel, and graded loam to gravel	3.75	5.0
Graded silt to cobbles	4.00	5.5
Shale, hardpan, and coarse gravels	6.00	6.0

b. Vegetatively lined swales

Cover	Range of Channel Gradient (Percent)	Permissible Velocity (Feet per Second)
Vegetative[a]		
(1) Tufcote	0 to 5.0	6
Midland	5.1 to 10.0	5
Coastal bermudagrass	Over 10.0	4
(2) Reed canarygrass	0 to 5.0	5
Kentucky 31 tall fescue	5.1 to 10.0	4
Kentucky bluegrass	Over 10.0	3
(3) Red fescue Redtop	0 to 5.0	2.5
(4) Annuals[b] Small grain (rye, oats, barley, millet) Ryegrass	0 to 5.0	2.5

[a]To be used only below stabilized protected areas.

[b]Used only as temporary protection until permanent vegetation is established.

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4.10.2.4 Check Dams

A check dam is a temporary structure of stone or logs that, when placed across a natural or man-made channel, is used to stabilize the grade or control erosion. Some specific applications of check dams include:

1. Temporary and permanent ditches or swales which for some reason cannot receive a nonerodible lining for the required length of time.

2. Temporary and permanent ditches or swales which require protection during the establishment of their vegetative linings.

3. Where a relatively rapid change in grade or elevation takes place which would endanger the stability of the ditch or swale.

Figures 4-45, 4-46, and 4-47 illustrate several different types of check dams. In designing a check dam the following factors should be considered:

1. Materials generally used in check dams include concrete, metal, rock, gabions, wood, and baled straw and hay. For other than short-term use, wood should be treated with perservatives.

2. The drainage area being serviced by the check dam should not exceed 10 acres.

3. The maximum height of a check dam should be 2 ft.

4. Spacing should be such that the toe of the upstream dam is at the same elevation as the crest of the downstream check dam (Figure 4-48).

5. Riprap may be necessary at the downstream side of the check dam to prevent scouring of the ditch or swale and to prevent undercutting of the dam.

6. Consideration should also be given to aesthetic qualities of the materials.

7. Check dams will usually require additional analysis of the channel design above and below the check dam.

8. Check dams should be located in a reasonably straight section of the channel.

Construction details to be considered are:

1. If a check dam is to be constructed from wood salvaged from the clearing operations, these logs should be 4 to 6 inches in diameter and of sound quality.

2. Logs should be driven a minimum of 18 inches into the channel bed (more if into a cohesionless soil).

3. Filter fabric can be incorporated into the upstream face of the check dam (Figures 4-45, 4-46, 4-47).

4. Stone check dams should be constructed of 2- to 3-in.-diam stones.

5. Check dams should be inspected periodically, especially after a significant rainfall.

FIGURE 4-45

LOG CHECK DAM - TYPE 1 (RICHARDS AND MIDDLETON, 1978)

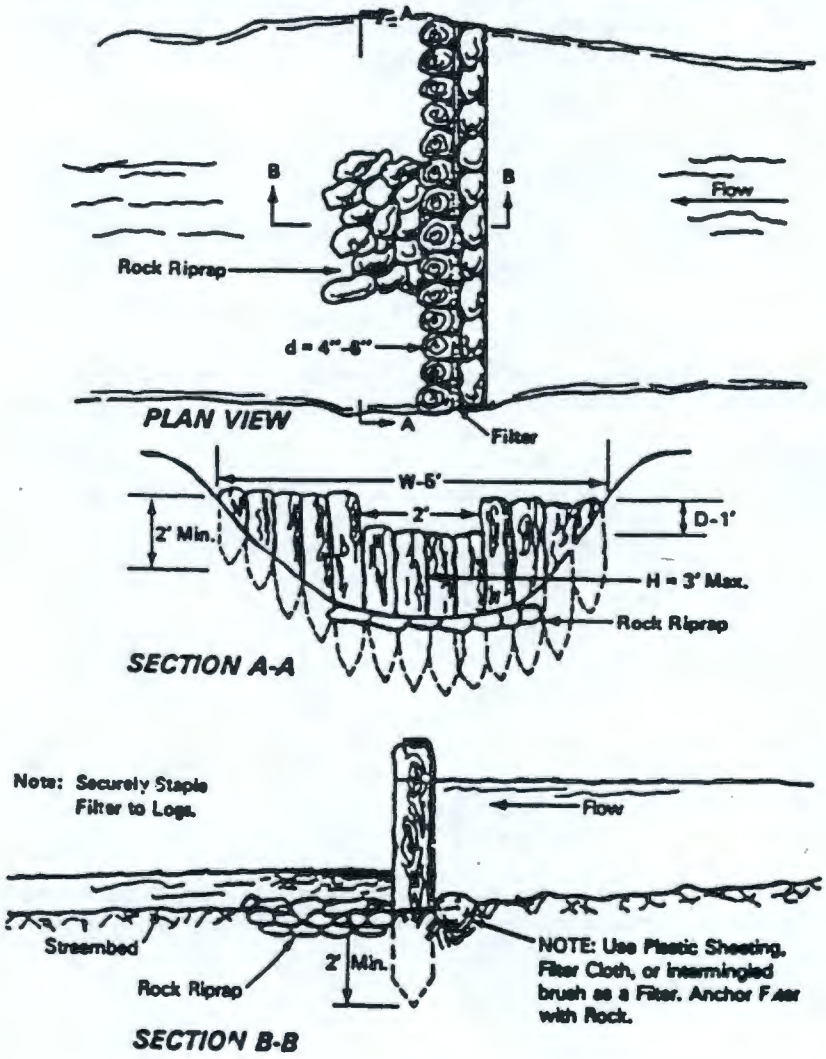


FIGURE 4-46

LOG CHECK DAM - TYPE 3 (RICHARDS AND MIDDLETON, 1978)

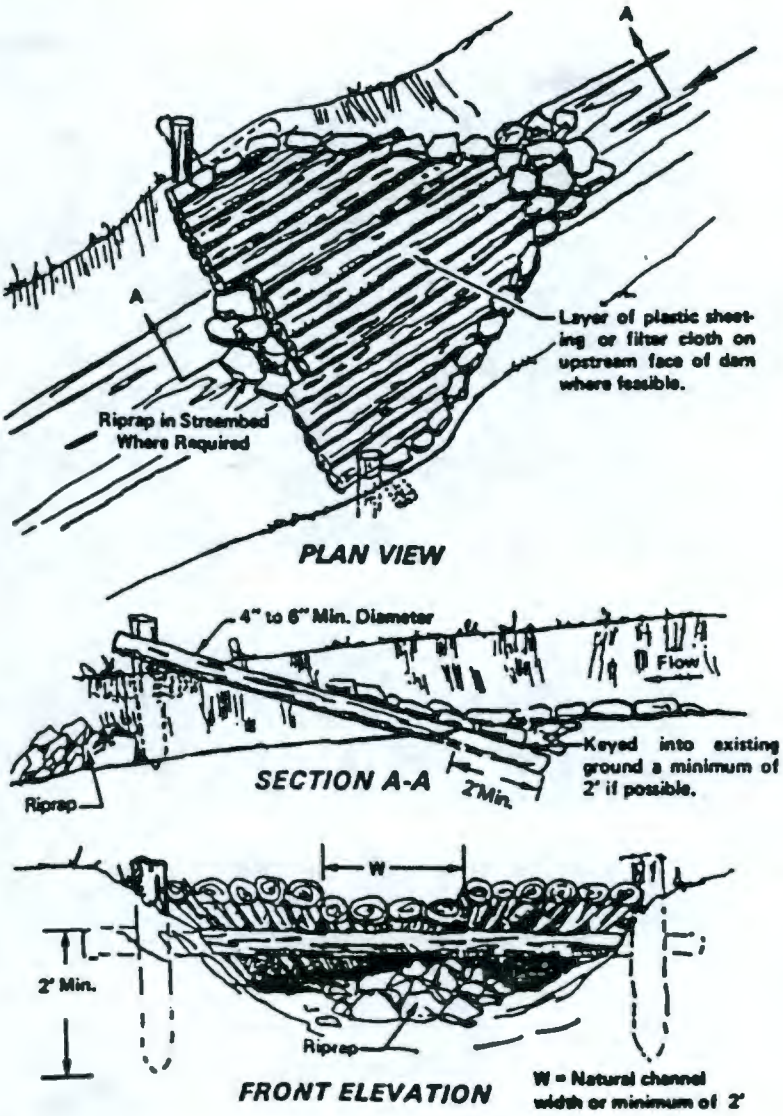


FIGURE 4-47

ROCK CHECK DAM
(VIRGINIA SOIL AND WATER CONSERVATION COMMISSION, 1980)

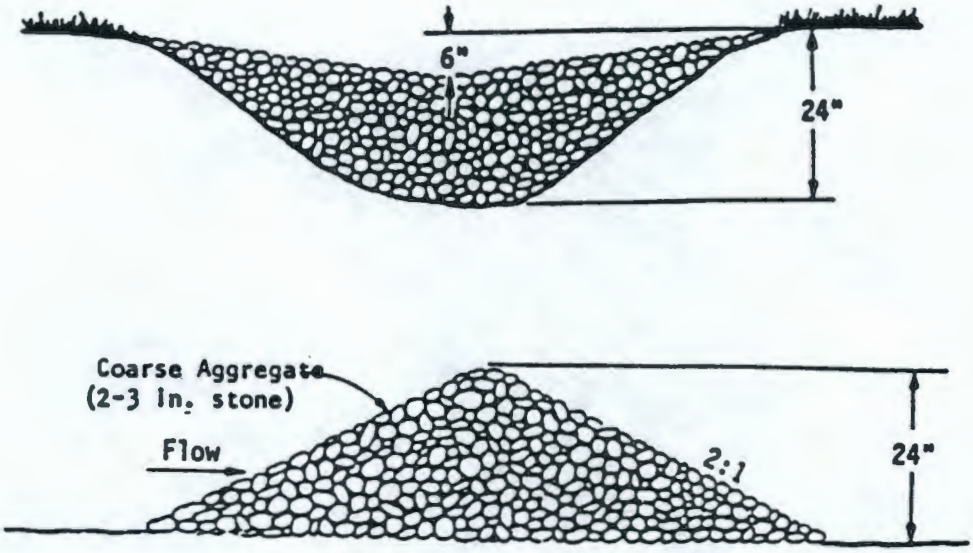
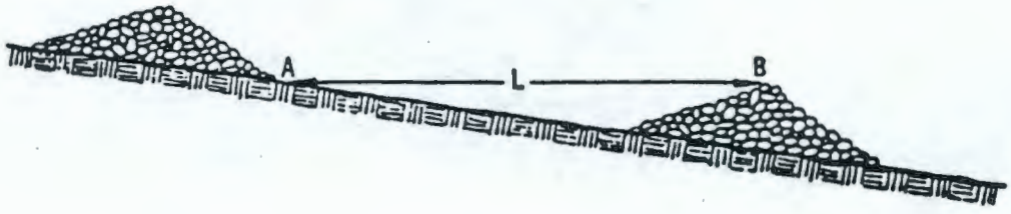


FIGURE 4-48

SPACING BETWEEN CHECK DAMS
(VIRGINIA SOIL AND WATER CONSERVATION COMMISSION, 1980)

L = The distance such that points
A and B are of equal elevation



4.10.2.5 Outlet Structures

The final links in a SWMP are the outlet structures. These outlet structures include pipes and/or chutes which provide an exit for a concentrated flow of surface runoff without causing erosion. In the case where this concentrated flow is conveyed to a relatively flat slope, then usually a simple pipe or channel outlet with the required outlet protection may be all that is required. Outlet protection is defined as methods and materials which prevent the flow from an outlet pipe, channel, or conduit from eroding the soil at the outlet structure and in the next channel reach. However, if a rapid change of elevation or grade exists at an outlet, then a downdrain structure is required. Design and construction criteria for outlet structures are presented in Appendix H.

4.11 Frost Action

An item of concern to the cover designer may be the potential for frost damage in cold climates. However, there is reason to believe that such damage can be prevented by proper design.

When a saturated soil freezes, the pore water undergoes a volumetric expansion of 9 percent. The soil mass as a whole will expand by a fraction of 9 percent, equal to the porosity. For example, a saturated soil of 50 percent porosity expands by 4.5 percent. Such uniformly distributed expansion should not have a significant disruptive effect, although repeated expansion and contraction over the years may cause slow movement down slopes, as pointed out by Lutton, Regan, and Jones (1979).

The distress that highways suffer during freezing weather arises from the phenomenon of frost heaving. This process involves the formation of sizable ice lenses within the soil, not simply the freezing of many minute pores to form a frozen soil mass. Frost heaving has been studied at great length, and there are many excellent published discussions of it. See, for example, Mitchell (1976), Oglesby (1975), and publications of the Highway Research Board cited in these two sources.

In brief, frost heaving requires three indispensable factors, any of which by its absence is sufficient to prevent the process. These are (1) frost-susceptible soils, (2) freezing temperature, and (3) a supply of water.

Frost-susceptible soils are those possessing to an appreciable degree both the properties of permeability and capillarity. The ice lenses that cause frost heaving grow as water migrates to them through unfrozen capillary channels but, having reached the lense, then freezes. Capillarity is required to draw the water through the soil. Permeability is required for it to be possible for appreciable quantities of water to flow. Because they possess both of these properties, the most frost-susceptible soils tend to be silts.

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The third indispensable element is a supply of water. In effect this means a water table. This may be normal or perched; if perched, it may be large or small in extent; but the essential requirement is a source from which the water flowing to the lense through the capillary system may be replenished. Even if conditions are favorable for the growth of ice lenses, without a water supply they cannot grow. They are starved, like a fire without oxygen.

It is the latter factor, a water table, that is unlikely to be present at a properly designed waste-site cover. If a sufficient pool of subsurface water is present close to frost-susceptible soils, frost heaving might develop. It should be preventable, however, by design and maintenance of a proper drainage system. No special design for frost heaving is required, only an awareness of its causes and the exercise of care to see that the three causative factors do not come together in a given cover system.

CHAPTER 5

CONSTRUCTION

Construction bears a close relation to design. The quality of the cover system depends on both. The best possible design will not deliver good results if it is not carried into effect by good construction. The designer, in turn, needs to be informed about construction practices and problems in order to prepare a realistic and constructible design.

Measures taken to insure that the actual construction meets the standards called for in the design come under the heading of construction quality control, which is treated in the next chapter. Construction organization, methods, and equipment are considered in this chapter.

5.1 Operational and Construction Guidance

The cover system's designer (or design team) should outline a set of operational and construction procedures to be followed in each of the three phases of cover construction:

- Site preparation
- Cover construction
- Site closure

There is not any single "best" procedural outline which can be efficiently prescribed to fit the variety of Superfund sites across the United States. An effective operational plan for a site in a humid region could prove needlessly restrictive for a cover constructed at an arid site. Therefore, the cover's construction and operational procedure, like the cover's design itself, must be based upon site-specific information in order to recognize all of the pitfalls associated with a particular site as well as to exploit any advantages.

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5.2 Phases of Cover Construction

5.2.1 Site-Preparation Phase

The site-preparation phase encompasses the span of time from the securing of the site up to the construction of the cover's first layer. Generally, the operations included in this phase include:

- Establishment of site security
- Initial clearing and grubbing
- Establishment of controlled surface drainage to prevent runoff of contaminants
- Establishment of the support facilities
- Establishment of internal access roads and soil stockpiles
- Precontouring site

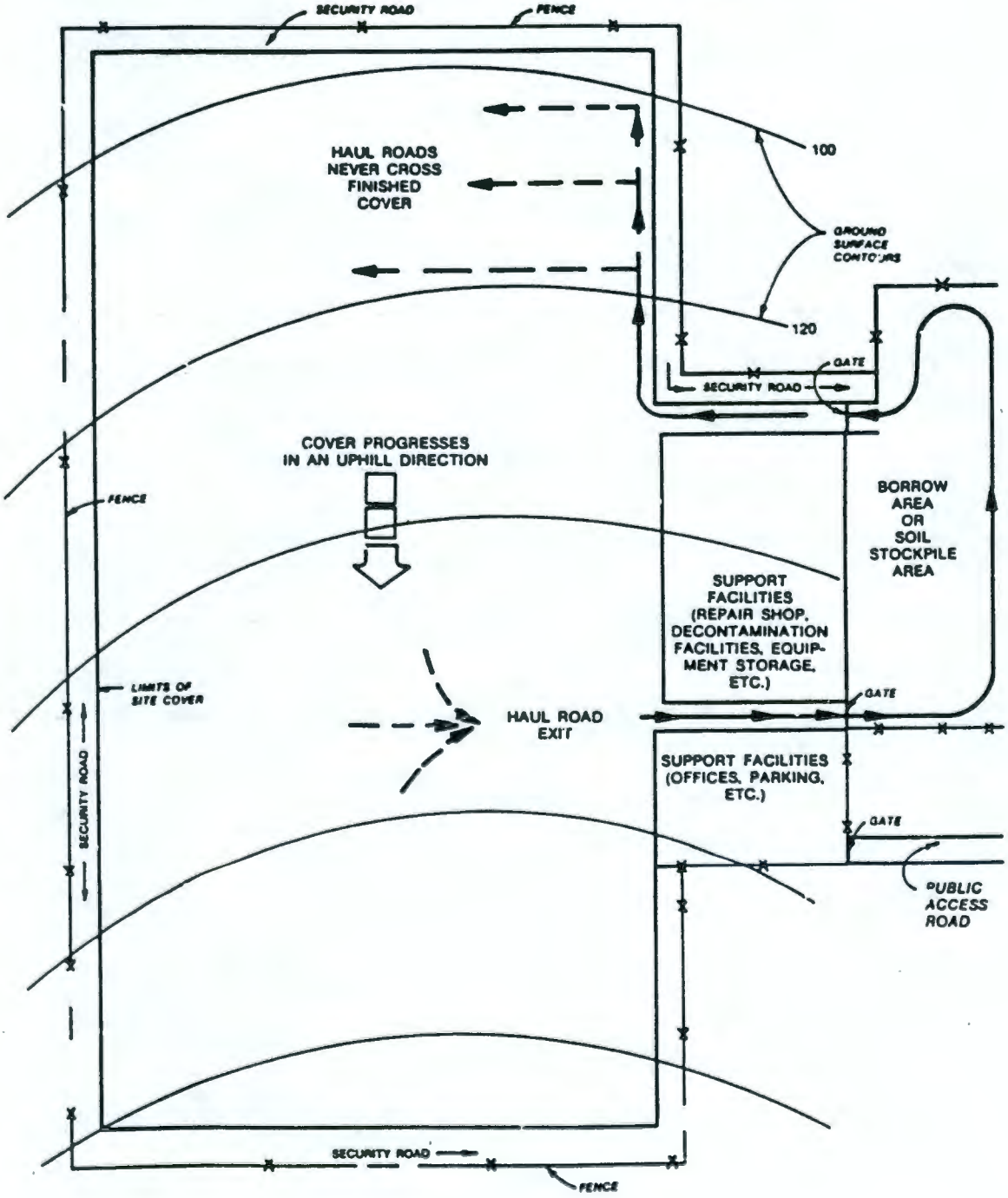
Since this Handbook deals with cover systems for CERCLA (Superfund) sites, it is assumed that a state or federally enforced site-security program will already exist at the site at the time the cover-construction contractor begins operations. It is a normal procedure for the construction contractor to assume responsibility for the security of the site shortly before or at the time he initiates operations. Normally, these security measures include surrounding the site with a security fence paralleled by a road for patrolling the fence. This fence should bear signs which clearly indicate that it is dangerous to enter the site and that there is limited access (no trespassing) to the site. Generally, a security program's aim is to prevent the inadvertent intrusion of the general public onto the site.

After the site has been secured, the site's clearing and grubbing operations are initiated. Clearing and grubbing are generally continual operations. Ideally, the clearing and grubbing operation should not proceed so far in advance of the construction operations that large denuded areas are created which will cause erosion or slope-stability problems. The amount the clearing program may precede construction will depend upon the severity of the site conditions causing or contributing to the problems. This initial clearing and grubbing should be enough to enable the contractor to establish his support facilities (offices, repair shop, decontamination facilities, etc.) and any internal access roads needed to reach the construction area, borrow pits, and areas for stockpiling soils (if needed) (Figure 5-1).

"Precontouring" a site is defined in this Handbook as establishing a uniform grade across the site (or portion of the site) as part of the surface water management plan (SWMP) or to provide a stable, suitable working surface from which to begin construction operations. The slope(s) established in this operation may or may not parallel the site's final contours. These initial

FIGURE 5-1

SIMPLIFIED SITE LAYOUT SHOWING TYPICAL CONSTRUCTION FEATURES



9 3 1 2 9 0 4 1 1 1 7 4

slopes are usually established by cutting down any high spots at the site and filling and compacting soil in the low areas. Also, precontouring the site may involve removing an area or layer of soil that is potentially troublesome, such as a layer of sandy soil or peat at the ground surface.

5.2.2 Cover-Construction Phase

5.2.2.1 Planning and Scheduling

The cover construction phase begins with the initiation of operations surrounding the actual construction of the cover layers. The procedural outline for this phase basically includes:

- Ongoing clearing and grubbing operations
- Establishment of the site's surface water management plan
- Cover construction plan outlining:
- - Construction processes associated with the installation of each cover element
- - Overall site plan showing the elevation of each of cover elements at any point on the site as well as their sequence of installation.
- Dust control measures
- Location of any soil stockpiles
- Area(s) suitable for carrying on operations during inclement weather (rain and freezing conditions)
- Types of equipment to be used for each construction process
- Traffic flow plan for the site

Because it is impractical (often impossible) to construct a cover element (layer) across an entire site (with the possible exception of the foundation layer) before beginning the next, the construction of each layer must be sequenced so that the leading edge of the lower layer is ahead of the upper layer (Figure 5-2). Since the finished slope of the final cover surface is designed to maximize surface-water flow, cover construction should proceed in an uphill fashion (Figure 5-3). In this manner, flow is maximized away from the construction area rather than toward it.

Traffic patterns on the final layer of soil should be across the slope to minimize the initiation of rills.

Care should be taken during construction to prevent accidental mixing of

FIGURE 5-2

SEQUENCING OF LAYERS DURING COVER CONSTRUCTION

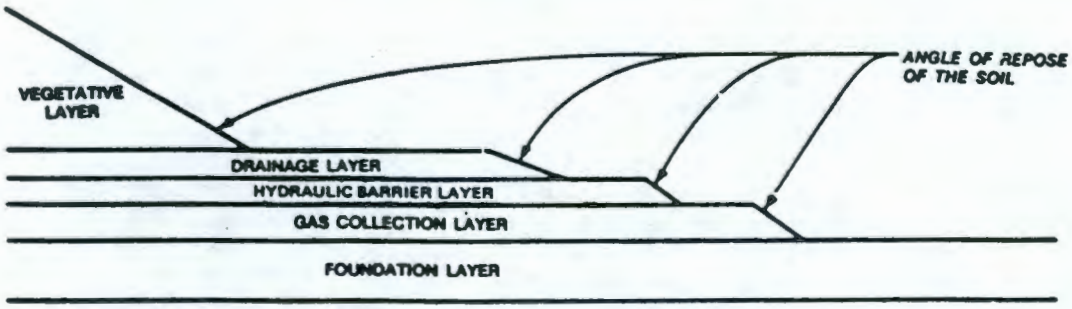
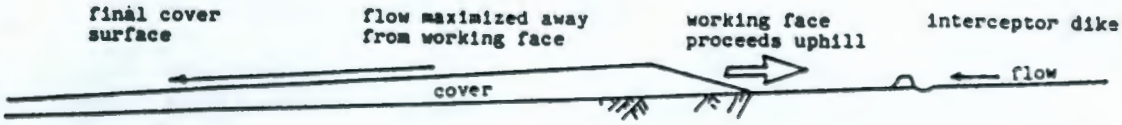


FIGURE 5-3

DIRECTION OF CONSTRUCTION



material from one layer into another layer. This is most likely to occur as a result of heavy rainfall during construction. If heavy rain does occur, the affected area near the working face should be cleaned up before construction proceeds. The flat area on top of a newly completed portion of a layer (see Figure 5-2) should be wide enough so that cleanup equipment can operate efficiently, and equipment used (see next section) should have low enough ground pressures so as not to cause rut formation. The most serious consequences of mixing would probably result from infiltration of clayey fines into a granular permeable layer. Clay should be compacted soon after placement to make it more erosion-resistant. (A compacted clay surface should be scarified or otherwide roughened before the next lift is placed upon it.) If heavy rainfall is anticipated, the clayey working face may be covered with plastic sheeting, or with a geotextile to reduce the erosive power of raindrops.

5.2.2.2 Equipment

A commonly overlooked factor which can have a great impact upon the success of a cover system is the equipment used. One problem may arise out of failure to recognize the effect a piece of equipment may have upon cover elements already constructed. For example, if a sheepsfoot compactor is used on a relatively thin sand drainage blanket overlying a gravel drain and separated by a geotextile, there is a good chance that the sheepsfoot roller will cause a rupture in the geotextile. With the separating effect of the geotextile gone, the gravel drain will clog. Another problem could originate from overlooking the impact that a change in equipment type could have on the quality of the cover. An example would be a contractor's choice to use a rubber-tired dozer instead of a crawler type to spread the protective sand layer over a geomembrane. Mobility and speed are gained in going to a wheeled-type dozer, but there is a substantial increase in ground contact pressure. If the sand buffer over the geomembrane were not thick enough to distribute this extra pressure safely, or the foundation beneath the membrane not strong enough, the geomembrane could be punctured or torn.

Table 5-1 presents a general overview of equipment capabilities as they relate to cover construction activities. This table should be used for general guidance only, as a particular type of equipment may rate better or worse depending upon what other types of equipment are also being used, as well as what types of soils and climatic conditions exist at the site. Basically, equipment used for cover construction can be grouped as:

- Excavators
- Earthmovers
- Compactors
- Specialty equipment

The primary function of an excavator is to break up and remove material but not haul it. Figures 5-4, 5-5, and 5-6 provide examples. Earthmovers, on the other hand, can excavate (to a degree) and move the soil from one place to another. However, the efficiency of these earthmovers varies with distance (Figures 5-7, 5-8, and 5-9). Compactors do what the name implies. Figures 5-10, 5-11, and 5-12 present examples and Table 5-2 provides guidance on their use. Equipment items that are unique from the standpoint of more efficiently performing the duties of several pieces of equipment combined, or that are designed to do primarily only one type of job, are designated as specialty equipment. Examples of specialty equipment are shown in Figures 5-13, 5-14, and 5-15.

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TABLE 5-1

APPLICABILITY OF EQUIPMENT TYPES TO VARIOUS OPERATIONAL FUNCTIONS

Operational Function	Equipment Type												
	Dozer		Scraper		Backhoe			Loader					
	Crawler	Rubber-Tired	Towed	Self-Propelled	Tractor	Excavator	Motor Grader	Crawler	Rubber-Tired	Compactor	Landfill Compactor	Power Shovel	Dragline
Site Preparation and Maintenance	G	F	F	F	F-P[c]	NA	G-F	G	F	NA	P	P	F-P
Excavate Cover Materials	E	F	E[a]	E[a]	E	E	NA	E	G	NA	P	E	E
Haul Cover Materials:													
1. 300 ft (91 m) or less	F	G	E[b]	G-F[b]	C	C	NA	F	G	NA	F-P	C	C
2. 300-1000 ft (91-305 m)	P	P	F	G	C	C	NA	C	C	NA	NA	C	C
3. More than 1000 ft (305 m)	P	P	P	E	C	C	NA	C	C	NA	NA	C	C
Spread Cover Materials	E	G	E-G	E-G	NA	NA	G	G	F	NA	F-P	NA	NA
Compact Cover Materials	G-F	G-F	NA	NA	NA	NA	NA	G-F	G-F	E	E	NA	NA
Shape Cover Materials	G-F	G-F	F-P	F-P	NA	NA	E	G	F	NA	P	NA	NA

E = Excellent; G = Good; F = Fair; P = Poor; C = Only in combination with other equipment; NA = Not Applicable

[a]Highly dependent upon site conditions and equipment size

[b]Economics of operation a prominent factor

[c]Depends on size of operation

FIGURE 5-4

BACKHOES

BACKHOE TRACTOR

Primary Use: Excavation of small-width trenches. Small-capacity excavation and hauling unit.

Advantages: Versatile piece of small equipment. Useful in construction of drainage ditches and trenches for gravel drains. Good mobility.

Disadvantages: Small size limits capacity. Hauling capabilities optimized when used in combination with trucks.

BACKHOE EXCAVATOR

Primary Use: Excavation below working level.

Description: Capacities 0.5-4 cu.yd.; ground pressure 6-15 psi; speed 2-2.5 mph.

Advantages: Greater capacity than backhoe tractor. Moves materials when it excavates them. Can dig harder materials than dragline. Greater reach, more articulate than power shovel.

Disadvantages: Must use in combination with trucks to optimize effectiveness. Slow rate of travel. Must be loaded on trailer to transport quickly.

FIGURE 5-5

POWER SHOVEL AND DRAGLINE

POWER SHOVEL

Primary Use:

Excavation above working level

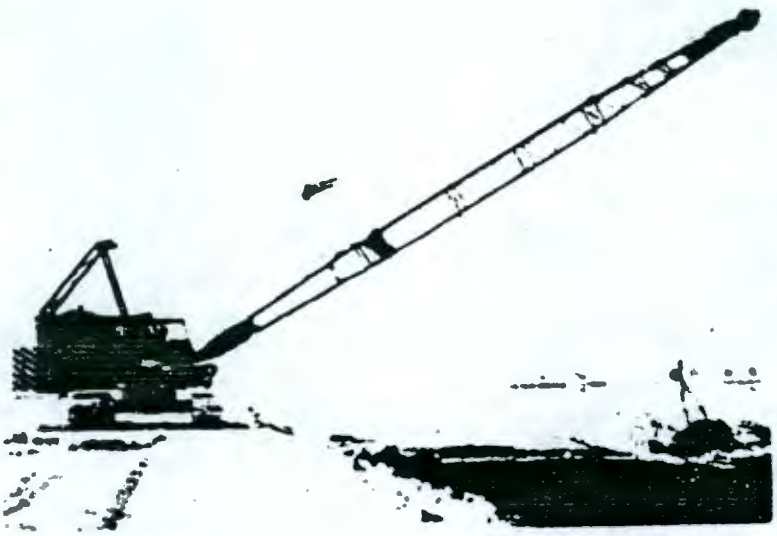
Capacities:

Commonly 4-14 cu.yd., larger capacities not uncommon. Typical excavation rates for average conditions 70-90 cu.yd./hr. per cu.yd. of bucket capacity.

Advantages:

Very versatile for mixing layered materials during excavation; can excavate much harder materials than dragline; larger capacity than backhoe excavator.

Disadvantages: Fairly accurate truck spotting required when loading. Excavates hard materials in large chunks that must be broken prior to compaction.



DRAGLINE

Primary Use:

Excavation below working level

Capacities:

Usually comparable to power shovel, though some draglines use larger buckets.

Advantages:

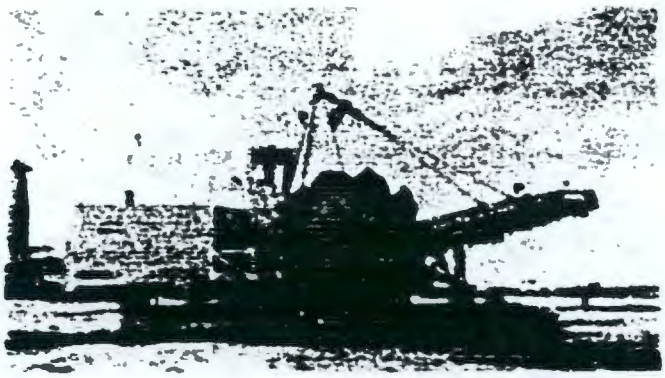
Very effective in excavating pervious materials from below water table; effective where borrow-pit bottom is too soft to support trucks or scrapers.

Disadvantages: Generally slower than shovels and scrapers; cannot excavate hard materials; less efficient than power shovel in mixing layered material in borrow pit.

FIGURE 5-6

CONVEYOR-TYPE EXCAVATOR

Primary Use:	High-volume excavation with direct discharge into hauling unit
Description:	Capacity 4,000-16,000 tons/hour; vertical cutting face 10-15 ft; conveyor length up to 60 ft.
Advantages:	High volume of excavation; good blending of material; enables selective excavation of horizontally stratified soils; can excavate horizontally or vertically.
Disadvantages:	Borrow areas must be relatively flat; slow travel speed; has difficulty with soils containing cobbles.



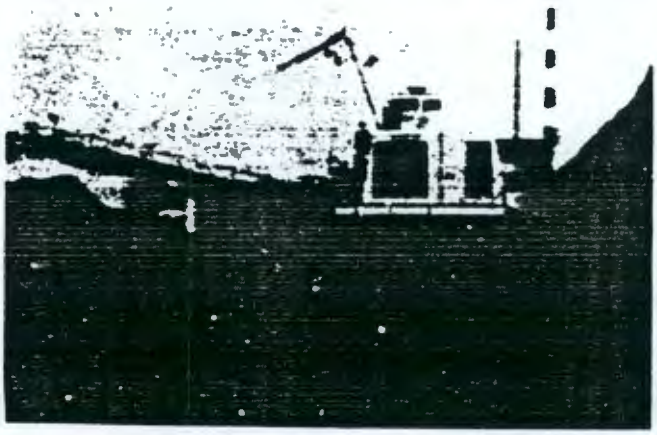


FIGURE 5-7

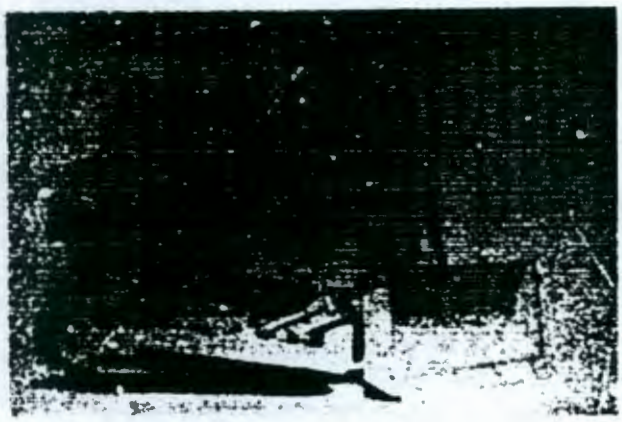
DOZERS

Primary Use: Pushing earth or other materials over short distances

Description: (Small and medium-sized tracked bulldozers) Weights 15,000-70,000 lb; horsepower 65-300 HP; ground contact pressures 8-13 psi (standard models) or 4-7 psi (low-ground-pressure models); speeds up to 7 mph.

Advantages: Very versatile machine employed in numerous construction uses; e.g., clearing and grubbing, helping to push-load scrapers and front-end loaders, ripping hard materials, finishing slopes, excavating access roads, assisting other mobile equipment by pushing or pulling. Blade may be angled horizontally and vertically.

Disadvantages: When working in close proximity to barrier cover layer (especially with geomembranes), great caution required to avoid puncturing barrier with blade or tracks. Similar cautions for other cover layers. Dozer has limited capacity for compacting and hauling material.



TRACKED DOZER

Available in numerous sizes, in standard and low-ground-pressure models

WHEELED DOZER

Used where speed and maneuverability are required. Small and medium-sized machines have speeds of 18-30 mph, turning radius 20-30 ft. However, ground contact pressures may be 20-25 psi.

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FIGURE 5-8

SCRAPERS (STANDARD, ELEVATING, AND TOWED TYPES)

Primary Uses: Excavation, hauling, depositing of soil materials

General Descriptions: Capacities 10-25 cu.yd.; weights 27-68 tons; ground contact pressures loaded, 45-65 psi; engine horsepower 150-350 HP.

Advantages: Rapid-moving type of excavation machinery; larger, faster machines can compete with trucks as hauling units. Scrapers can be used to selectively excavate horizontally stratified soils and deposit materials in even layers, sometimes eliminating need for additional spreading equipment. Breaking up of material as it is excavated facilitates later compaction.

Disadvantages: May prove unsatisfactory in very soft materials; tandem-powered, push-pull models required in such environments. Adverse grades may require tandem-powered models. Scraper's efficiency as hauling unit decreases with distance.

STANDARD TYPE

Self-propelled; available in single-engine and tandem-powered models (second engine for rear tires). When used alone, single-engine model is best suited to flat terrain and favorable excavation conditions. In adverse conditions single-engine scraper is usually pushed or pulled by crawler dozer or another scraper. Tandem-powered scraper reduces this dependence but sometimes operates more efficiently in push-pull configuration with another scraper or dozer.

ELEVATING TYPE

Does not rely solely on cutting edge and scooping action of bowl to load self; employs loading elevator to aid in loading and unloading soil. Available in single-engine and tandem-powered models. Generally has good capability for working alone. Soils undergo more mixing (blending) than with other scraper types.

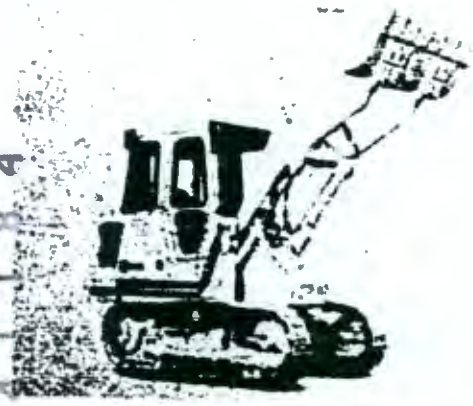
TOWED TYPE

Usually towed by a crawler tractor, wheeled tractor, or self-propelled scraper where excavation conditions require good traction and haul distance is relatively short.

FIGURE 5-9

FRONT-END LOADERS

Primary Use: Excavate and load cover materials; haul small quantities short distances.



TRACKED TYPE

Description:

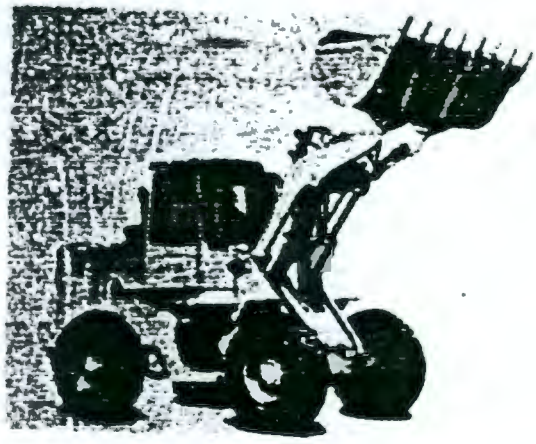
Weight 15,700-55,000 lb.; ground contact pressures 5-12 psi; capacities 1-3.75 cu.yd.; horsepower 50-200 HP.

Advantages:

Low ground contact pressures available with tracked models. Can be used in combination with trucks to increase haul efficiency.

Disadvantages:

Does not spread over as well as dozer. Slower moving than wheel-type loader. Lower bucket capacity than wheel-type loader.



WHEEL TYPE

Description:

Weight 21,000-60,000 lb.; ground contact pressures 11-46 psi; capacities 1.25-5 cu. yd.; horsepower 50-250 HP.

Advantages:

More mobile, greater bucket capacity than tracked type. Can be used in combination with trucks to increase haul efficiency.

Disadvantages:

Higher ground contact pressures

FIGURE 5-10

SHEEPSFOOT ROLLERS

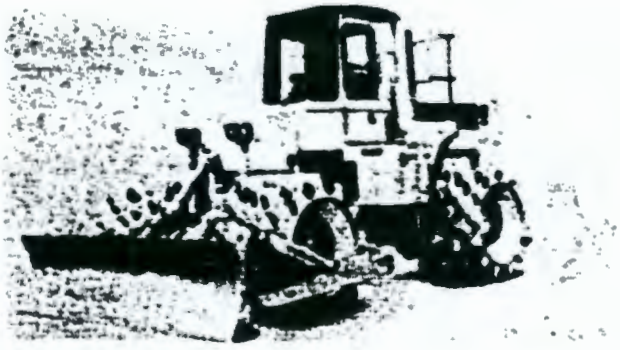
Primary Use: To compact fine-grained soils or coarse-grained soils with appreciable plastic fines

Descriptions: Weights 2,000-4,000 lb. per foot of drum length; ballasted with water or sand and water.

Advantages: Kneading, churning, and tamping action mixes soil and water better than other compaction equipment (this does not preclude proper processing of material prior to compaction, however); produces good bond between lifts; breaks down weak rock or cemented soils.

Disadvantages: Leaves surface rough and loose, and therefore susceptible to wetting by rains or surface waters. Compacts to shallower depth than other equipment. Effectiveness diminished in compacting soils containing cobbles or large rock fragments. Self-propelled rollers sometimes cause shearing or laminations in fill.

TOWED MODEL

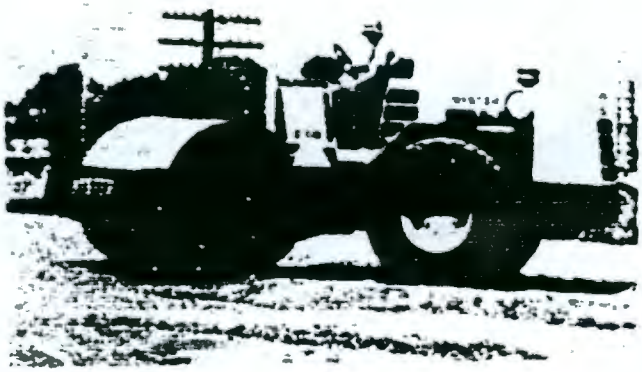


SELF-PROPELLED MODEL

FIGURE 5-11

VIBRATORY STEEL-WHEEL DRUM ROLLER

Primary Use:	To compact cohesionless materials or materials where a smooth finished surface is desired (such as asphalt or soil-cement)
Typical Specifications:	Vibration: between 1,100 and 1,500 vpm; dynamic force: not less than 40,000 lb. at 1,400 vpm; weights 7,000-20,000 lb.; compaction speed: not to exceed 1.5 mph.
Advantages:	Greater densities can be obtained in cohesionless soils than with tamping or rubber-tired equipment. Fill may be flooded with water to improve compaction.
Disadvantages:	May cause degradation of soil or rock-fill particles and create layers of fines.



9 3 1 2 9 0 4 1 1 8 6

FIGURE 5-12

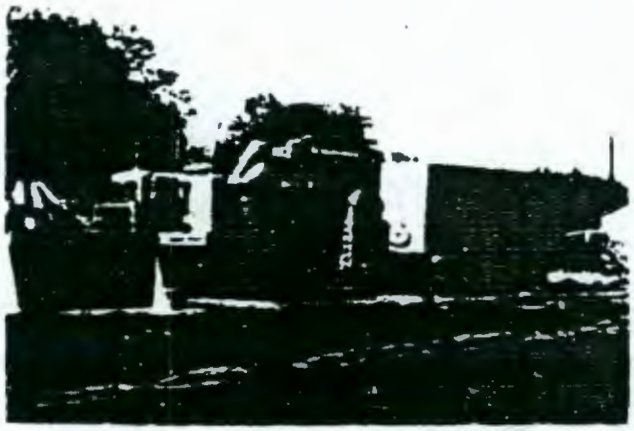
RUBBER-TIRED ROLLERS

Primary Use: To compact cohesive and cohesionless soils where a smooth compacted surface is desired

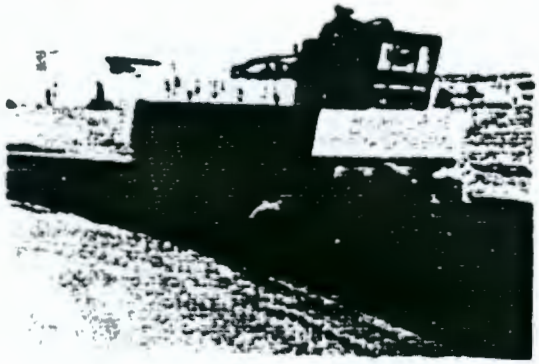
Description: Weights 18,000-25,000 lb.; wheel spacing, distance between adjacent tires not to exceed 1/2 of tire width.

Advantages: Compacts to greater depths than sheepsfoot roller. Produces relatively smooth compacted surface which is rain-resistant. Effective in compacting in closer quarters than sheepsfoot. More effective than sheepsfoot in compacting cohesive soils containing large particles. Wet areas of fill can be determined by observation of roller rutting.

Disadvantages: Compacted surfaces must be scarified before placing next lift. Not as effective as sheepsfoot roller in breaking down soft rock or mixing fill material.



LARGE-WHEEL, TOWED MODEL



SMALL-WHEEL, SELF-PROPELLED MODEL

Courtesy Bros Division of American Hoist and Derrick Co.

TABLE 5-2

COMPACTION EQUIPMENT GUIDANCE

Equipment type	Applicability	Requirements for compaction of 95 to 100 percent Standard Proctor maximum density: Compacted lift thickness, in. (cm)	Passes or coverages	Dimensions and weight of equipment			Possible variations in equipment
				Soil type	Foot contact area, in. (cm^2)	Foot contact pressures, psi (MPa)	
Sheepsfoot rollers	For fine-grained soils or dirty coarse-grained soils with more than 20% passing No. 200 mesh; not suitable for clean coarse-grained soils; particularly appropriate for compaction of linings where bonding of lifts is important.	6 (15)	4-6 passes for fine-grained soil; 6-8 passes for coarse-grained soil	Fine-grained soil PI > 30	5-12 (32-77)	250-500 (17-34)	For large projects (in order to maximize width of pass), drum of 60-in. diam. (152 cm), loaded to 1.5-3 tons per lineal ft (43.7-87.5 kN per lineal m) of drum generally is used; for smaller projects, 40-in. dia. (101 cm) drum, loaded to 0.75 to 1.75 tons per lineal ft (21.9-43.7 kN per lineal m) of drum is used; foot contact pressure should be regulated so as to avoid shoring the soil on the third or fourth pass.
				Fine-grained soil PI < 30	7-14 (45-90)	200-400 (1.4-2.8)	
				Coarse-grained soil	10-14 (64-90)	150-240 (1.0-1.7)	
				Efficient compaction of wet soils requires less contact pressures than the same soils at lower moisture contents.			
Rubber tire rollers	For clean, coarse-grained soils with 4-8% passing No. 200 mesh.	10 (25)	3-5	Tire inflation pressures of 60 to 80 psi (0.41-0.55 MPa) for clean granular material or base course and subgrade compaction; wheel load 10,000-25,000 lb (80-110 kN); tire inflation pressures in excess of 65 psi (0.45 MPa) for fine-grained soils of high plasticity; for uniform clean sands or silty fine sands, use large size tires with pressure of 40 to 50 psi (0.28-0.34 MPa).			Wide variety of rubber tire compaction equipment is available; for cohesive soils, light-wheel loads such as provided by rubble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased; for cohesionless soils, large-size tires are desirable to avoid shear and rutting.
	For fine-grained soils or well graded, dirty coarse-grained soils with more than 8% passing No. 200 mesh.	6-8 (15-20)	4-6				
Smooth wheel rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixture.	8-12 (20-30)	4	Tandem type rollers for base course or subgrade compaction, 10-15 ton weight (89-133 kN), 300-500 lb per lineal in. (3.4-5.6 kN lineal cm) of width of roll roller.			3-wheel rollers obtainable in wide range of sizes; 2-wheel tandem rollers are available in the range of 1-20 tons (8.9-178 kN) weight; 3-axle tandem rollers are generally used in the range of 10 to 20 tons (89-178 kN) weight; very heavy rollers are used for proof rolling of subgrade or base course.
	May be used for fine-grained soils other than in earth dams; not suitable for clean well-graded sands or silty uniform sands.	6-8 (15-20)	6	3-wheel roller for compaction of fine-grained soil; weights from 5-6 tons (44-53 kN) for materials of low plasticity to 10 tons (89 kN) for materials of high plasticity.			
Vibrating baseplate compactors	For coarse-grained soils with less than about 12% passing No. 200 Mesh; best suited for materials with 4-8% passing No. 200 mesh, placed thoroughly wet.	8-10 (20-25)	3	Single pads or plates should weigh no less than 200 lb (0.89 kN); may be used in tandem where working space is available; for clean coarse-grained soil, vibration frequency should be no less than 1,800 cycles per minute.			Vibrating pads or plates are available, hand-propelled, or self-propelled single or in gangs with width of coverage from 1.5-15 ft (0.45-4.57 m); various types of vibrating-drum equipment should be considered for compaction in large areas.
Crawler tractor	Best suited for coarse-grained soils with less than 4-8% passing No. 200 mesh, placed thoroughly wet.	10-12 (25-30)	3-4	No smaller than D8 tractor with blade, 34,500 lb (153 kN) weight, for high compaction.			Tractor weight up to 60,000 lb.
Power tamper or rammer	For difficult access, trench backfill; suitable for all inorganic soils.	4-6 in (10-15 cm) for silt or clay; 6 in. (15 cm) for coarse-grained soils		30 lb (0.13 kN) minimum weight; considerable range is tolerable, depending on materials and conditions.			Weights up to 250 lb (1.11 kN); foot diameter 4 to 10 in. (1.27-3.93 cm).

Source: EPA/530/SW-870, "Listing of Waste Impoundment and Disposal Facilities"

FIGURE 5-13

LANDFILL COMPACTOR

Primary Use:	Spreading and compacting cover materials
Description:	Weights 45,000-70,000 lb.; horsepower 200-300 HP; drum width 3-4 ft; number of drums: 4; drum diameter 4-5 ft.
Advantages:	Relatively high-speed compactor; dual-purpose machine (spread and compact); undercarriage less vulnerable than dozer tracks; variety of wheel types available.
Disadvantages:	Not as good as dozer for spreading or excavating cover materials; wheels chop as well as compact, may tend to shear soil.

LANDFILL COMPACTOR

DETAIL OF WHEEL

FIGURE 5-14

TRENCHER

Primary Use: Excavating narrow slit trench for anchoring geomembranes and placing utility or drainage lines

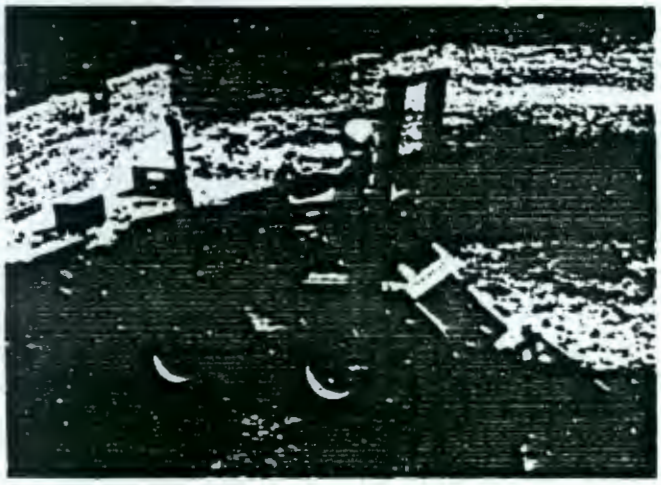
Advantages: Lightweight, compact, and maneuverable; some tractor-mounted models have a backhoe attachment.

Disadvantages: A specialized piece of equipment with limited field of usefulness

HAND-OPERATED MODEL

Description:

Weight 500-1,100 lb.; horsepower 5-10 HP; trench widths 3-12 in.; trench depths 24-60 in.; ground contact pressure 5-10 psi.



TRACTOR-MOUNTED MODEL

Description:

Weight 1,500-10,000 lb.; horsepower 15-100 HP; trench widths 3-24 in.; trench depths 60-95 in.; ground contact pressure 10-40 psi.

FIGURE 5-15

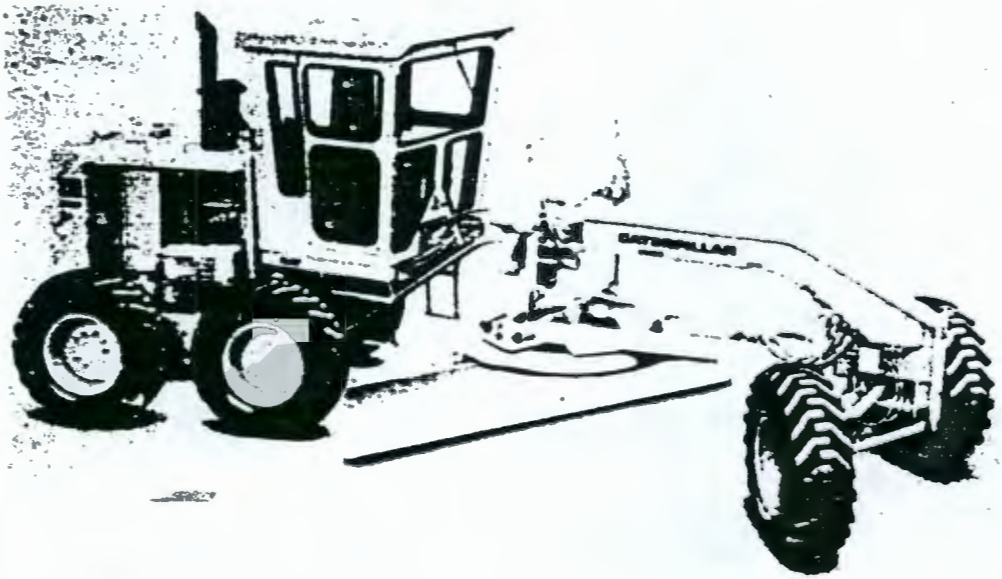
MOTOR GRADER

Primary Use: Shaping and smoothing cover

Description: Weight 25,000-55,000 lb.; horsepower 125-250 HP; speed 25-30 mph.

Advantages: Can be used to dig "V" notch anchor trenches for geomembranes. Performs road maintenance. Accurate method of shaping slopes and obtaining grades. Available with variety of blade widths.

Disadvantages: Relatively restricted field of applications.



5.2.3 Site Closure Phase

Site-closure activities are basically twofold in nature.

- The institutional care and maintenance required to stabilize the cover system are performed.
- The cover system is monitored to ascertain that it is performing its design function.

Theoretically, the closure phase begins when the final stretch of cover layer is installed. However, since the cover's final elevation and grade are not reached all at once, but rather in a progressive state of completion (Figure 5-2), there is some overlap between the construction and closure phases. While a new section of the cover system is being constructed, closure operations are underway to stabilize and monitor the portion of the cover already completed.

Institutional care and maintenance activities include repairing damage from erosion, slope failures, subsidence or any occurrence, foreseen or unexpected, which is not directly related to a design flaw. These problems by nature do not require perpetual active mantenance.

5.3 General and Special Construction Operations

Most of the construction operations carried on during the installation of a cover system are standard ones common to earthwork in general. A partial list of construction operations and functions is presented in Table 5-3. It is outside the scope of this Handbook to describe common construction operations. Excellent sources of information on construction are Nichols (1962) and Church (1981).

Briefly discussed below are certain special construction operations pertinent to installation of waste-site covers.

5.3.1 Mixing and Placement of Soil-Cement

When constructing a soil-cement layer, mixing may be done in place or in a central plant. Mixing in place involves spreading the portland cement over the soil and dry-mixing or blending it into the soil evenly. This is normally accomplished by means of an agricultural disk harrow. Water is introduced into the soil-cement mixture, and mixing continues until the soil-cement is uniform in color and free from wet and dry streaks.

Central-plant mixing involves mixing the cement, soil, and water in a batch plant similar to that used to produce concrete mixes. The soil-cement mixture is transferred to dump trucks, which take it to its final destination,

where it is placed in lifts of 6 to 8 in. thickness. Generally, the central-plant mixing operation creates a higher-quality soil-cement, as tighter quality controls can be exercised. However, acceptable results have been obtained using the mixing-in-place method.

TABLE 5-3

PARTIAL LIST OF CONSTRUCTION OPERATIONS AND FUNCTIONS

Earthwork	**Control Operations**
Borrow Pit	Surveying
Excavation	Inspection
Screening	Sampling
Mixing	Testing
Watering	**Service Operations**
Disking	Transportation
Loading	Fueling
Hauling	Lubrication
Cover Site	Maintenance and Repair
Dumping	Field Sanitation
Placing	Water Service
Spreading	Dust Suppression
Compacting	Trash Disposal
Installation	**Management Functions**
Pipes	Scheduling
Tiles	Supply management
Membranes	Personnel management
Asphalt emplacement	Accounting
Concrete emplacement	Payroll
Soil stabilization operations	Record keeping
Vegetation operations	Field laboratory operation
	Security
	Safety

After mixing and placing, the soil-cement is compacted by means of a rubber-tired, sheepsfoot, or steel-wheeled compactor.

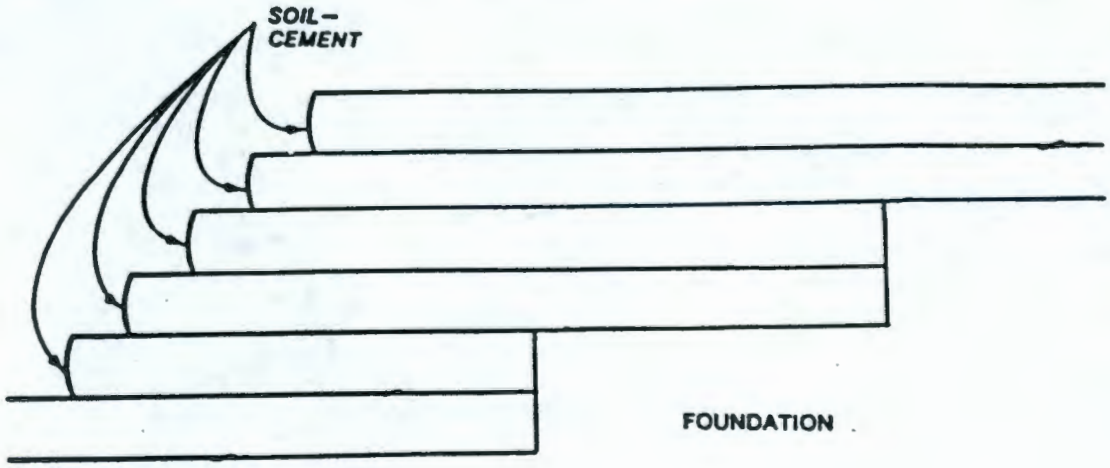
If a stair-step configuration (Figure 5-16) is used because of steep slopes, the bond strength between successive layers becomes important. In general, bond strength decreases with increasing delay between placement of successive layers. No more than one to three hours should elapse between construction of successive layers. Therefore, some operational planning is required to meet this time limit. Also, bond strength is enhanced if one or more of the following procedures is used:

- Scarify the completed layer with a power broom or spiked-tooth tool, to a depth of about 1/4-inch, within one to three hours after construction of the layer.
- Sprinkle dry cement (about one pound per square yard) on top of the moistened completed layer just prior to construction of the successive layer.
- Use a sheepsfoot roller rather than a steel-wheeled or rubbered-tired compactor. The dimpled texture left by the sheepsfoot may key the succeeding layer to the lower layer.

After the soil-cement has been placed and compacted, the layer is immediately covered, to prevent an excessive loss of water. Some materials commonly used for this purpose include waterproof paper, plastic sheeting, moist straw,

FIGURE 5-16

STAIR-STEP CONFIGURATION



moist earth, and bituminous materials (RC-250, MC-800, RT-5, and asphalt emulsions). The application rate for the bituminous materials varies from 0.15 to 0.30 gallon per square yard.

5.3.2 Compaction of Foundation Layer

Normally the compaction procedure proceeds along the following outline:

- Preparation of the area to be compacted
- Adjustment of the water content
- Compaction of the material
- Scarification of compacted soil if another layer is to be compacted over it and a bond is desired

The initial preparation of the site usually involves the clearing and grubbing of any trees, stumps, brush, or other vegetation that would have an adverse effect on the cover system. Spraying the ground with a soil sterilant could also be necessary, as some hydraulic barrier materials are susceptible to plant penetration (such as thin asphalt and synthetic membranes). If this clearing and grubbing leaves the surface in an unsuitably loose condition or if the existing surface is to be incorporated into the foundation layer (as is usually the case), then the preparation phase will include scarifying the surface (as necessary) with an agricultural type disk harrow to facilitate its compaction. Even if compaction of the site's surface is not specified, it is a good practice to scarify it to assure a good bond between it and the rest of the foundation layer. If the site's surface is not to be compacted, then the final phase of preparation would be to deposit the material forming the first layer (if more than one is required) of the foundation layer. This is usually accomplished by bottom-dumping out of scrapers or end-dumping from trucks.

After the material to be compacted is in place and prepared, then its water content is adjusted to that specified for the desired density. The water content of the soil is adjusted by disking the soil and air drying it, if it is too wet, or spraying water (usually by trucks equipped with tanks and sprayers) and disking until the required moisture content is uniformly achieved. A good field indication that the soil is at the proper moisture content is how it reacts to the passage of the compaction equipment. If excessive rutting or sinking of the compaction equipment into the lift occurs, this could mean that the water content is too high. The absence of any "spring" in the soil after the passage of the compactor could indicate that the water content is too low. Rapid moisture determinations can be made in the field with the nuclear moisture-density gauge (see sec. 6.5 and Appendix G).

The deposition of loose lifts and their compaction should be a highly coordinated affair. Ideally, these operations should occur at the same time. As one lane of soil is being compacted, an adjacent lane of material is being

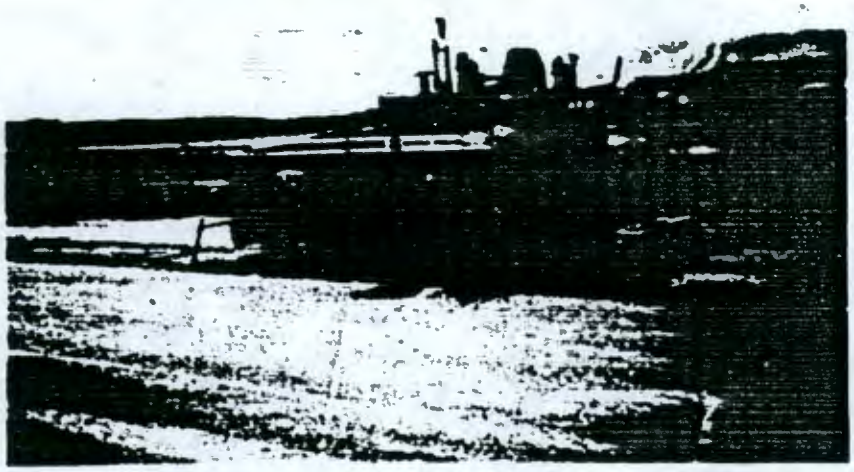
deposited. If another layer is to be compacted over a oreviously compacted layer, then the lower layer should be scarified to ensure a good bond between them.

5.3.3 Placement of Asphalt Concrete

Asphalt concrete is placed using conventional highway paving machines modified (Figure 5-17) as necessary to work on the slope. This modification may entail hooking a winch (at the top of the slope) onto the paving machine for moving up the slope or attaching it (with chains or cables) to another piece of equipment at the top of the slope for moving across the slope. The paver is supplied by dump truck, front-end loader, a moving conveyor, or a combination of these.

FIGURE 5-17

ASPHALT PAVING MACHINE



Compaction is accomplished using steel-wheeled rollers, rubber-tired rollers, and vibratory steel-wheeled rollers.

5.3.4 Installation of Polymeric Barriers

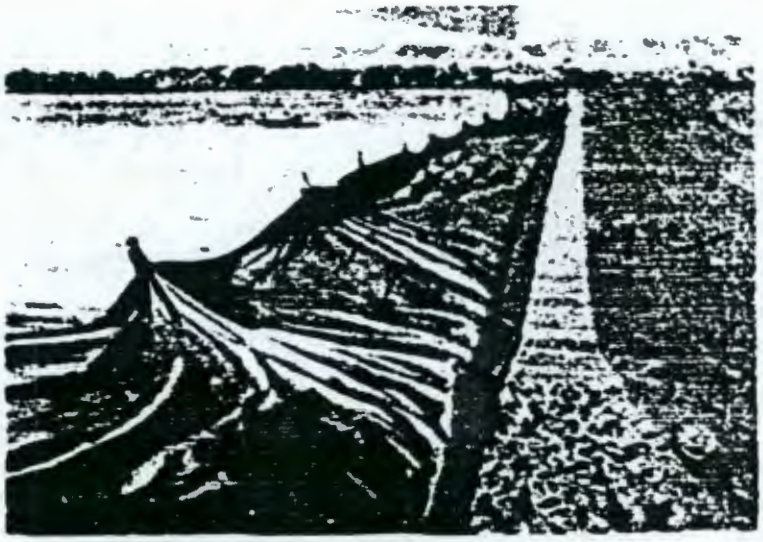
Construction of a polymeric barrier usually takes place as follows:

- Panels are spread by hand or machine (Figure 5-18) and anchored
- The panels are aligned and weighted down (Figure 5-19)
- Field seams are constructed (Figures 3-16 through 3-19, Chapter 3)

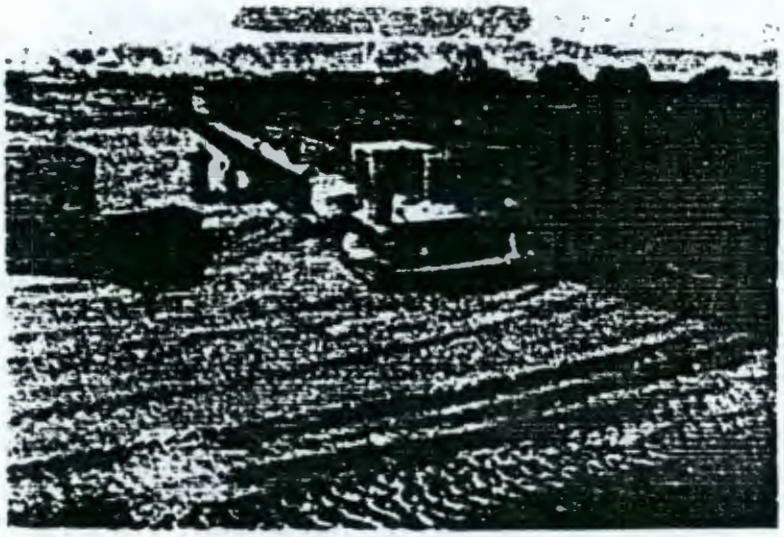
9 3 1 2 9 0 4 1 1 9 6

FIGURE 5-18

SPREADING POLYMERIC SHEETING



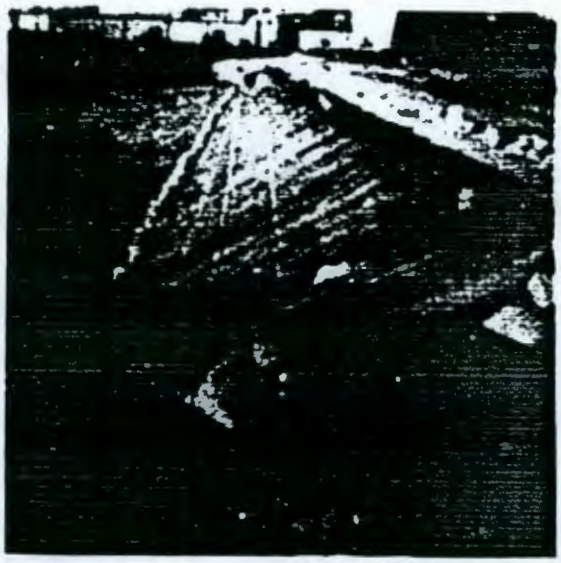
a. Manually



b. Mechanically

FIGURE 5-19

SHEETING ALIGNED AND WEIGHTED



- Seams are inspected (Figure 5-20)
- Cover material is applied over the geomembrane (Figure 5-21)

The figures cited above show membrane installation at liner rather than cover sites because the number of sites where geomembranes have actually been installed in waste-site covers is small. However, see Figure B-5 in Appendix B, "Case Histories," for an illustration of a membrane being placed at a cover site. The question of how steep a slope a geomembrane may be laid on is discussed in section 4.6.3.4.

Although possibly more economical than buying the machinery needed to spread the polymeric material, laying the membrane out by hand has its shortcomings. The wind is usually the primary enemy as it can catch the membrane and create a "membrane sail" which is difficult to hold down. Also it takes a highly coordinated effort to get a long line of men to correctly align the sheeting.

Although there are many seam testing devices available (infrared, ultrasonic, air wand, etc.) the one device that seems to have the confidence of the designers is the vacuum-box tester. However, it is a time-consuming method that can only test a short length of seam at one time. Also, the designer must decide if this degree of assurance that his seam is completely watertight is needed.

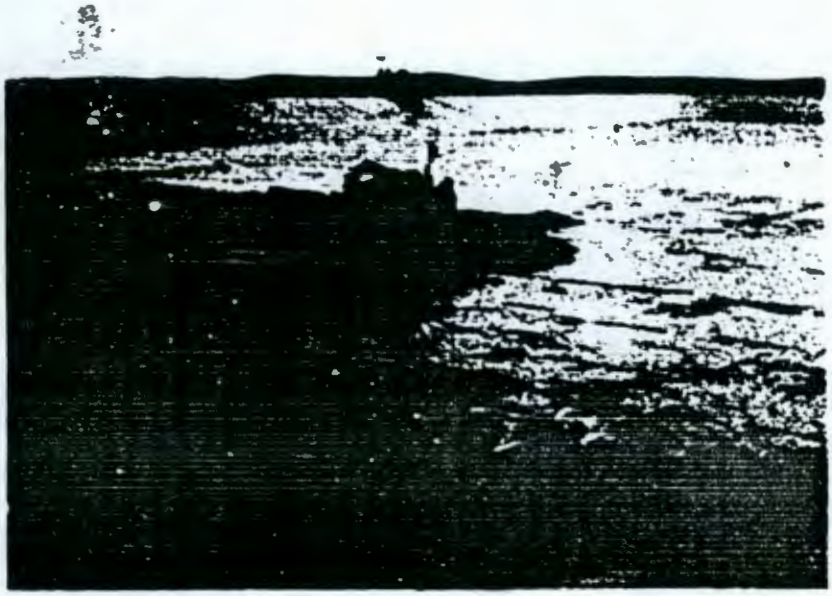
9 3 1 2 9 0 4 1 1 9 8

FIGURE 5-20

INSPECTION OF SEAMS (VACUUM-BOX SEAM TESTER)

FIGURE 5-21

COVER APPLIED OVER GEOMEMBRANE



Note: these views show liner rather than cover installations.

9 3 1 2 9 0 4 1 2 0 0

Polymerics are susceptible to some mechanical failure mechanisms that are not present in the other barrier materials. They are:

- Fold strain (Figure 5-22a)
- Tension from wind and anchorage (Figure 5-22b)
- Expansion-contraction forces (Figure 5-23)

As the wind flows across the membrane it tends to lift it. In large open areas, the wind forces can be considerable. If the end of the polymeric is left unanchored, damage could result from the flapping of the membrane caused by the wind. This problem can be handled by:

- Anchoring the trench (Figure 5-24)
- Weighting down the edges with sandbags
- Using a wind cowl (Figure 5-25)

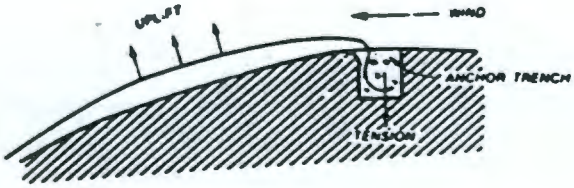
Some polymeric materials, such as HDPE, exhibit a high degree of expansion and contraction when exposed to variations in temperature. This creates additional stresses at the seam. However, these stresses, by themselves, may not be enough to break a field seam that is correctly constructed. Therefore, emphasis should be placed on the quality of the field seams in these types of materials. Also, these materials should be covered as quickly as possible to reduce this phenomenon.

Protection of the barrier during construction is very important. In general, all of the different types of hydraulic barriers require a protective cover. Usually this is a minimum of 6 in. of sand. However, with the frequency of machinery-generated punctures many manufacturers are raising this to 12 in. The Asphalt Institute recommends a 12-in. minimum protective cover requirement. This sand buffer may be replaced by a geotextile if it can be shown that the geotextile will sufficiently protect the membrane from puncture.

FIGURE 5-22

GEOMEMBRANE FIELD STRESSES

a. FOLD STRAIN



b. UPLIFT FROM WIND

FIGURE 5-23

EXPANSION-CONTRACTION PHENOMENON

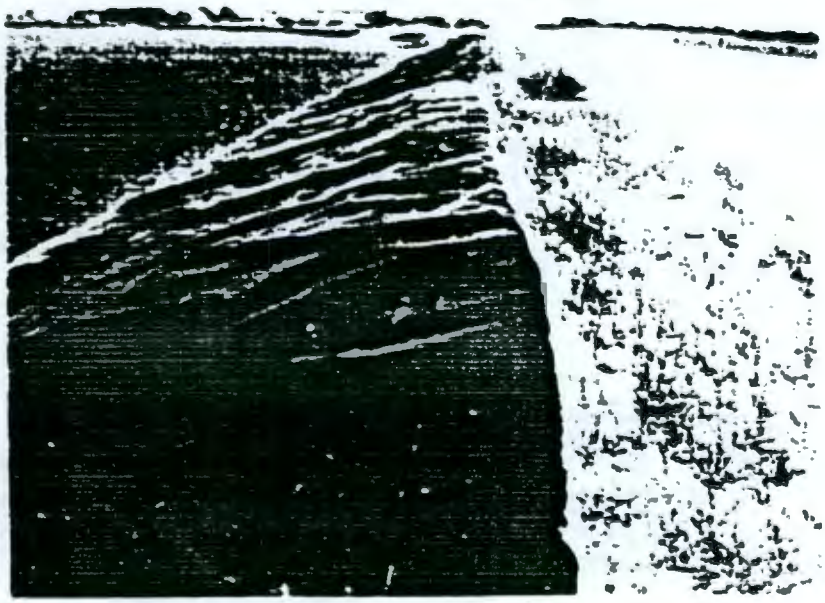


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FIGURE 5-24

ANCHORING DETAILS

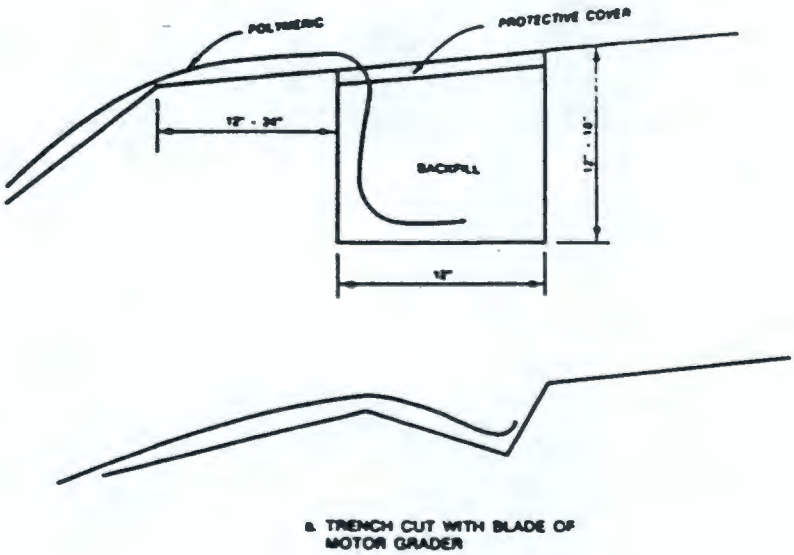
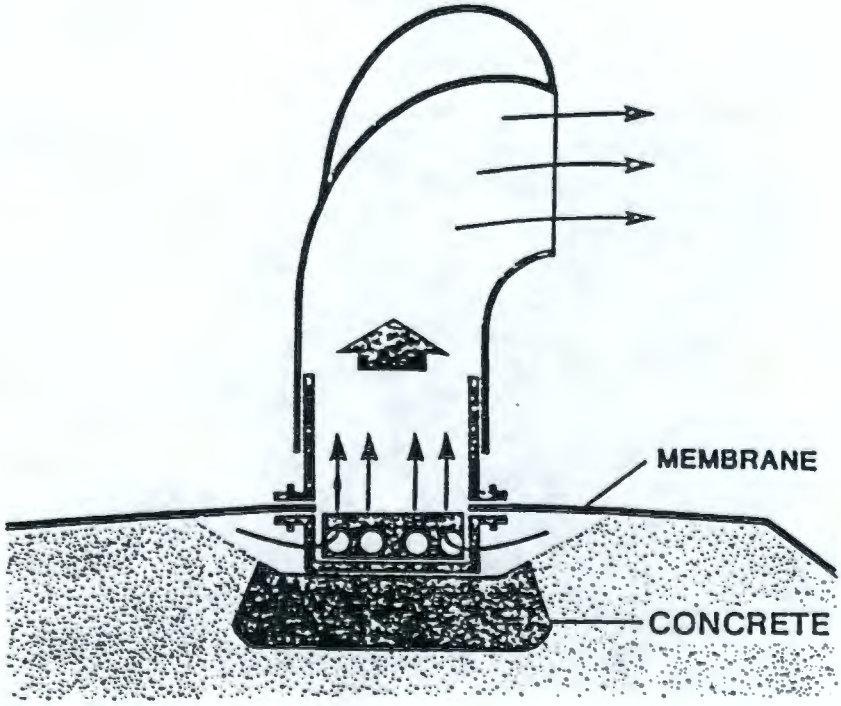


FIGURE 5-25

WIND COWL



CHAPTER 6

CONSTRUCTION QUALITY CONTROL

6.1 Construction Organization

Three groups contribute to the quality control of construction of covers for uncontrolled waste sites: (1) design, (2) construction, and (3) inspection groups.

The design group analyzes and designs, and produces the plans and specifications which are the written standard of quality for the cover(s) to be constructed. This group also verifies the design as the construction group exposes site media. All feedback from the construction and inspection groups is interpreted, and changes to the design are made when necessary.

The construction group provides all workmanship and materials. As site media are exposed, findings are reported to the design group. The construction group is the element in the quality-control system that physically achieves the standard of quality.

Members of the inspection group sample, test, observe, and document during construction, and unacceptable workmanship or materials is reported to the construction group. The inspection group provides feedback to the design group when possible. In the quality-control system the inspection group assures that the standard of quality has in fact been achieved by the construction group.

This quality-control system works best when all three groups interact and communicate for their mutual benefit. It also works best when all three groups report to a single higher authority, so that none of the three groups holds a subordinate position to another. When these conditions are met and the three groups work as a team, a synergistic effect results that is beneficial to all.

The higher authority referred to above, which might generally be called the site manager, can complement this synergistic organization. Intelligent scheduling, to allow inspection-group functions to be performed on a particular block of work while the construction group is busy on a different block of work, is an example. The site manager must also enforce the absolute nature of the standard of quality at a CERCLA site. That standard of quality must never be compromised. This standard is the site manager's responsibility as well as that of all three groups. The site manager must enforce the tenet

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that cost-effectiveness is a consideration only if the standard of quality is achieved. Such direction by the site manager will greatly aid the three groups by relieving them of the need to weigh quality versus cost-effectiveness.

6.2 Quality-Assurance/Quality-Control of Construction

Quality control of construction of covers for uncontrolled waste sites, as considered here, pertains to the physical construction of the cover but not to any site characterization nor to the design. Quality assurance of construction of covers for uncontrolled waste sites includes those actions by EPA, its local agency (if there is one), and the site manager which assure that the quality-control procedures for the construction will in fact assure that the standard of quality is achieved. In effect quality assurance is merely quality control of the quality control.

The quality-control procedures recommended for the construction of covers for uncontrolled waste sites include tests and observations. The difference between a quality-control test and a quality-control observation is merely a matter of the formality of the method involved. As an example, consider the quality-control procedures necessary to assure that a geomembrane seal has been bonded properly. An observation of 100 percent of the bonded seam would reveal any large fishmouths, large anomalies, or incorrectly sealed portions. The use of the air-lance method for 100 percent of the bonded seam would reveal smaller fishmouths, anomalies, and incorrectly sealed portions undetectable to the eye. This air-lance method is considered a quality-control test.

6.3 Quality-Control Observations

Quality-control observations are made continually by the inspection group while it observes the construction group work and while it actively performs its inspection functions. Quality-control observations of particular concern for the construction of covers for uncontrolled waste sites are organized by construction process and discussed below.

6.3.1 Site Preparation

The process of site preparation includes clearing, grubbing, stripping, and grading. The primary purposes for this activity are (a) preparation of the uncontrolled waste site for excavation and/or embankment placement, (b) construction of haul roads, and (c) altering the site drainage patterns. The following observations should be made and documented:

- Observations of the exposed ground surface within the site limits, following stripping, as part of site media confirmation. Normally, only visual-manual field identification procedures will be necessary (ASTM Designation D-2488). If an unexpected material or zone configuration is encountered, then more formal tests may be necessary.

- Observation of ground-surface contouring measurements to confirm adherence to the planned drainage pattern.

- Observation of the performance of the surface drainage system, during the first significant rainfall, to identify erosion or ponding problems.

6.3.2 Excavation

The preparation of an uncontrolled waste site may involve (a) excavation below the ground surface and/or (b) the stripping and shaping of a natural or man-made depression. The following observations should be made and documented:

- Detailed observations should be made of the exposed walls and floor for the purpose of site media confirmation. These observations should be supplemented by confirmation tests for those features that conform to the site characterization studies. Photographs are often of value. The tests will usually consist of field consistency tests and those tests required for USCS classification, i.e., gradation and/or Atterberg limits. More extensive testing may be necessary if an unanticipated material or zone configuration is encountered. Undisturbed samples and engineering-properties tests may be justified, with additional samples tested for index properties. Changes from expected site characteristics should not only be recorded, but immediately reported to the permittee's group responsible for the design function, for possible revision of the design.

- Observations should be recorded of construction surveys involving locations, slopes of walls, and slopes of floors. Conformance with planned slopes should be noted.

- During and after construction, visual observations, supplemented by surveying where necessary, should be made and recorded of excavation-related soil movements. These recordings should include heaving and/or cracking of the floor, and slaking, sloughing, creep, sliding, or other movements of the side walls. Again, photographs may be of great documentary value. Survey monuments, placed at the start of construction, should provide documentable data.

- Observations should be recorded of erosion controls for conformance with plans. These observations may include perimeter ditches and/or dikes and the placement of any spray-on erosion-inhibiting material, including the material's identification and application rate.

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6.3.3 Foundation Preparation

If an earthfill embankment is used to partially or completely enclose a waste site, the natural foundation and abutments must, as discussed in Engineer Manual 1110-2-1911 (Dept. of Army, 1977), (a) provide positive control of underseepage, (b) provide satisfactory contact with overlying compacted fill, and (c) minimize differential settlements and thereby prevent cracking in the fill. The observations made and recorded during foundation preparation should include:

- The stripping to assure that all soft, organic, or otherwise undesirable materials are removed. Softness may be checked by a hand penetrometer or similar device for a very relative strength estimate. Proof-rolling by construction equipment is often used to locate soft areas.

- The soil and rock surfaces for smoothness, adequate cleaning, and filling of rock joints and depressions.

- The construction of underseepage cutoffs, if used, to check required depth, materials encountered, backfill materials used, and proper placement of backfill. If compacted fill is used, it should be observed as for other fills as discussed below.

6.3.4 Compacted Earthfill

Compacted earthfill barriers may be used to partially or completely enclose a waste site. When used they may include a compacted-soil hydraulic barrier and a compacted granular hydraulic-conductor layer. When finished they may be overlain by a vegetation-supporting layer.

The waste contained by the barrier system may consist of solid wastes with moist soil backfill, which may eventually become saturated with water, or in the case of a surface impoundment, it may consist of a high-water-content slurry or sludge. If appreciable steady-state seepage is expected, then internal seepage-control features such as filter drains and underseepage control measures may be needed. The system may contain a hydraulic barrier, such as a geomembrane, supported by a compacted, low-permeability cohesive soil. It may also contain a hydraulic conductor, usually a granular filter material of high permeability.

The observations and tests that should be made (Dept. of the Army, 1977; and USBR, 1974a and 1974b) and recorded during compacted fill placement, using cohesive or granular soils are:

- The quality of the borrow materials must be tested. The source of the borrow may be a natural borrow pit or a stockpile of soil from a trench excavation. Two or more soils may be blended to produce a desired gradation or plasticity. Samples of the borrow materials

should be tested for USCS classification (gradation and/or Atterberg limits) and for natural water content. If admixes are blended into the natural soil, the application rate and uniformity of mixing should be observed and documented.

- Atmospheric conditions should be recorded. Compaction specifications often place restrictions on work performed just after a rainfall, during very hot or windy weather, or during freezing conditions.

- Equipment type, size, and compatibility with the soil type must be evaluated and recorded. For cohesive soil, a sheepsfoot roller, a tamping roller, or a rubber-tired roller may be used. For clean, granular soil, a vibratory roller is appropriate. As given in Engineer Manual 1110-2-1911 (Dept. of the Army, 1977), items to be checked and recorded include: (a) for a sheepsfoot roller, drum diameter and length, empty weight and ballasted weight, arrangement of feet and length and face area of feet, and yoking arrangement; (b) for a rubber-tired roller, tire inflation pressure, spacing of tires, and empty and ballasted wheel loads; and (c) for a vibratory roller, static weight, imparted dynamic force, operating frequency of vibration, and drum diameter and length.

- The uncompacted or loose lift thickness should be measured at several locations in a layer of fill. Both actual thickness and uniformity of lift placement are of importance. Loose lift thicknesses of (a) 6 to 8 in. for a sheepsfoot roller, or (b) 9 to 12 in. for a 50-ton rubber-tired roller are usual for cohesive soils; while clean, granular soils should have loose lifts of (c) 6 to 15 in. when using a vibratory roller or 50-ton rubber-tired roller, or (d) 6 to 8 in. when using a crawler tractor (Dept. of the Army, 1977). Measurements are usually made with a marked staff or shovel blade, although survey levels should be made every few lifts for verification and documentation. All level survey points should be referenced to the site grid so that comparisons of lift thickness can be made directly.

- Compactive effort and uniformity of compaction should be observed and recorded. Compactive effort can be revised by changing the number of passes of the roller, the size and weight of the roller, and/or lift thickness. For cohesive soils (a) six to eight passes of a sheepsfoot roller or (b) four coverages of a 50-ton rubber-tired roller are usual; while for a clean, granular soil (c) three or four passes of a vibratory roller or (d) three to six coverages of a crawler tractor are usual (Dept. of the Army, 1977). Uniformity of coverage should be closely observed, particularly at fill edges and in turnaround areas. When a crawler tractor is used, the coverages must be by the tracks of the tractor.

- Compacted density and water content should be measured and recorded. The coordinate location of each test and the elevation of the ground surface should also be measured. The latter is a check on lift thickness, and when a retest of unacceptable fill is necessary, serves to verify that no additional fill has been placed.

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- Laboratory compaction tests should be made of samples of the same fill soil whose field density and water content were measured in the item above. The effectiveness of the compactive effort in the field is referenced to the laboratory compaction test. Specifications for compaction of cohesive soil and "dirty" granular soil require achievement of a minimum percentage of the maximum density, at a water content within a specified range and related to the optimum water content, as determined by the specified laboratory compaction test procedure. For clean granular soils, which densify more readily under vibration than under impact, a minimum relative density or a minimum percentage of the laboratory maximum dry density is usually specified. This involves comparison of the density of the field-compacted soil with the maximum and minimum densities for the same soil developed in a specified laboratory procedure.

6.3.5 Liner-Type Materials and Geotextiles

The construction of a cover for an uncontrolled hazardous waste site may include the construction processes involved in liner material or geotextile installation. The hydraulic-barrier layer of the cover system is expected to provide a permeability smaller than a required value. When this permeability cannot be effectively achieved in a compacted soil fill layer, then off-site materials may be used. The off-site materials may consist of bentonite, portland cement, asphalt, lime, or similar materials that are admixed throughout or are mixed with only the surface lift of the compacted soil of the barrier. The barrier may also be a spray-on material or a geomembrane. Geotextiles may also be used as a filter aid or for soil reinforcement, e.g., to enhance slope stability or cover strength.

The tests and observations that should be made and recorded during liner-material or geotextile installation are generally material-dependent:

- For all off-site materials used (liner materials and geotextiles) the type and supplier's identification for the material should be recorded. Lot numbers or their equivalent are often useful in tracing materials of questionable quality to specific manufacturing procedures.

- For bentonitic and admixed-material layers these tests and observations should be those whose results can be correlated with expected values of field permeability of any soil layer, i.e., field density tests and observations of layer thickness. Where permeability is a significant consideration, laboratory permeability tests on field-compacted specimens ("plugs") are preferable to reliance on density/saturation correlations with laboratory-compacted specimens. The hole resulting from the test must be filled and repaired. (See tests and observations in the previous subsection on <u>Compacted Earthfill</u>.)

- The tests and observations for the installation of a portland cement or asphalt liner are not within the framework of soils engineering. References describing these tests and observations include Dept. of Army, 1971; Asphalt Institute, 1978 and 1979.

- For admixed materials, the spreading and mixing or blending equipment and procedures should be observed and recorded. Reference should be made to industry standard methods, to manufacturer's recommended procedures, or other descriptions of the state of the art for the methods.

- For admixed materials, the application rate should be observed and recorded. Methods for verifying the application rate, such as calibration of spreading devices, should also be recorded.

- For admixed materials, compaction of the soil-admixture blend should be observed, tested, and recorded in the same manner as described earlier for Compacted Earthfill. Soil classification tests, observations of lift thickness and of uniformity of rolling, observations of the suitability of blending and compacting equipment, and the comparison of field density (and water content, if applicable) with the specified laboratory control test, should all be made and recorded.

- For spray-on materials, the observations and tests include identification of the material, verification of manufacturer's quality tests, application-equipment suitability, application-technique comparison with state-of-the-art directions, application rate, application thickness, and uniformity of coverage.

- For geomembranes or geotextiles, the supplier's materials identification marks should be compared with the purchase-order or catalog descriptions. The smoothness of the placement surface, and its freedom from objects that might puncture the material, should be inspected. If required, test specimens may be cut from the field sheets; this will require patching, and the patching itself should also be observed and recorded. The method of placement of the material should be recorded and supplemented by photographs if possible. The seams should be inspected at numerous locations and the required seam overlap measured and recorded. The method of sealing the seam, whether thermal or adhesive, should be observed and recorded; all seam formation should be closely inspected. Seam-integrity tests, if specified, should be made and recorded, including notation of the locations of the tests. The entire placed material should be systematically inspected for imperfections or tears, and the results of the inspection recorded.

6.3.6 Hydraulic Collector System

The final cover may contain a permeable layer above the hydraulic barrier. Its function is to change the direction of the percolating water from a

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downward movement to a horizontal movement toward a nearby collector drain. Usually it is formed of a clean granular material placed directly on the surface of the impermeable hydraulic barrier. The surface of the barrier is sloped toward the collector system, usually located at the perimeter of the disposal unit. Observations and tests that should be made and recorded for this feature are:

- The surface of the base for the permeable layer should be inspected and observations recorded. Imperfections include soft soils, organic materials, the lack of specified admix or spray-on material, or leaks in a geomembrane.

- The amount and direction of slope of the permeable layer base should be verified and recorded. This will usually involve standard surveying techniques.

- The clean granular materials used in the permeable layer should be tested for gradation, particularly for the presence of undesirable fines. Comparison should be made to the specified gradation requirements.

- The placement, compaction, field density testing, and relative density testing should be performed and recorded as described above for Compacted Earthfill.

6.4 Quality-Control Sampling

Quality-control samples must be drawn on a systematic basis in order to justify confidence in test results. This systematic basis for sampling, for the purpose of testing, requires further discussion. The statistical sampling procedures described below are based in part on similar discussions in Hald (1952) and American Society for Testing and Materials (annual).

The method and frequency of sampling and testing in construction have traditionally been based on intuitive decisions of the sampler or his superiors. The purpose of sampling and testing is to provide data for evaluation of a portion of the work. Unless sampled by probability, or random, sampling methods, the result is often a biased and nonrepresentative estimate of a quality characteristic. Frequency of sampling and testing can only be rationally discussed in statistical-analysis terms. It is a function of desired level of confidence, maximum error or percent error, and the actual variability of the tested quality characteristic in the sampled portion of work. Comparison of standard and alternative test methods can be made on the basis of sample sizes needed for equivalence of confidence levels.

6.4.1 Frequency of Sampling and Testing

There is an inherent variability in measurement data for any specified

quality characteristic of any soil mass, whether natural or construction-processed. Variability in measurements occurs as a result of (a) material composition variability, (b) placement (formation) process variability, and (c) measurement process variability. All measurements contain variability from all three causes combined.

Each individual measurement of a quality characteristic may be considered to be one of a "countably infinite" number of similar measurements that could be made in a universe of the material. The difference or error between the measured value and the "true" or reference value is the sum of components, an accuracy (systematic or calibration) error and a precision (random) error. This can be written as (ASTM, annual):

$$X = \mu_R + \delta + \varepsilon \tag{6.1}$$

and

$$\delta = \mu_R - \mu_P \tag{6.2}$$

where

X = numerical value of a measurement
μ_R = true or accepted reference level of the property of the material to be measured
μ_P = the expected value or the average of many observations recorded for the process
δ = correction for consistent or systematic error of the measurement process at the reference level μ
ε = correction for random deviation about the average of the observations μ_P

<u>Accuracy</u> refers to the degree of agreement of individual measurements, or the average of a large number of measurements, with a "true" or accepted reference value. This definition implies the idea of a consistent deviation, or <u>systematic</u> or <u>bias</u> error, which is a fixed or common contribution to error in each of a set of measurements. <u>Precision</u> is the degree of mutual agreement among individual measurements of a consistent material made under prescribed, like conditions. The <u>imprecision</u> of measurement may be characterized by the standard deviation of the errors of measurement.

In Equation 6.1, the δ-term for correction for systematic, or accuracy, error is the sum of corrections from each of the three causes of nonrandom variation and is written:

$$\delta = \delta_M + \delta_P + \delta_T \tag{6.3}$$

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where

δ_M = correction for systematic error due to material composition
δ_P = correction for systematic error due to placement process
δ_T = correction for systematic error due to testing process

Because the effects of material composition, placement process, and testing process are interrelated, it is not usually possibly to differentiate these in a group of measurements. If the material-composition and placement-process effects are combined into a <u>material quality</u> effect, then:

$$\delta_Q = \delta_M + \delta_P \tag{6.4}$$

and

$$\delta = \delta_Q + \delta_T \tag{6.5}$$

where

δ_Q = correction for systematic error of the measurement process at the reference level μ_R due to the material quality (the combined effects of material composition and placement process).

The precision term of Equation 6.1, ε, is a random effect, and is the combination of random effects due to the three causes discussed above. The statistical variance, σ_0^2, of a group of measurements of a characteristic of a consistent material using a consistent test method is the sum of the variance due to the three causes of random variability. This may be given as:

$$\sigma_0^2 = \sigma_M^2 + \sigma_P^2 + \sigma_T^2 \tag{6.6}$$

and defining

$$\sigma_Q^2 = \sigma_M^2 + \sigma_P^2 \tag{6.7}$$

then

$$\sigma_0^2 = \sigma_Q^2 + \sigma_T^2 \tag{6.8}$$

where

σ_0^2 = overall variance

σ_M^2 = variance due to material composition

σ_P^2 = variance due to placement process

σ_T^2 = variance due to testing process

σ_Q^2 = variance due to material quality

If the variance due to a particular testing process, σ_T^2, is known, or can be estimated, then its effect on the overall variance, σ_0^2, can be evaluated from Equation 6.8 as:

$$\sigma_0 = \sigma_Q \quad 1 + \left(\frac{\sigma_T}{\sigma_Q}\right)^2 \tag{6.9}$$

where

σ_0 = total standard deviation
σ_Q = quality standard deviation
σ_T = testing standard deviation

When comparing alternative test methods, the effect of different standard deviations of the test methods on the overall standard deviation should be considered. It can be seen from Equation 6.9 that when material quality is uniform (low σ) the precision of the test method (σ) is of great importance. However, when material quality is not uniform (high σ) the relative precision of one test method (σ) versus another is of little overall importance.

6.4.2 Types of Sampling

Probably the most satisfactory method to the engineer concerned about sampling all parts of the block is a combination of (a) stratified random sampling and (b) systematic sampling with a random start.

If a universe, or block, consists of, or can be divided into, a group of strata, then a random sample can be drawn from each stratum instead of drawing a single random sample from the entire population. This procedure is called <u>stratified random sampling</u>. The division of a soil mass or a construction process into blocks is a form of stratified random sampling.

A popular sampling method is <u>systematic sampling with a random start</u>. This method involves the selection of successive sample units at uniform intervals of time, distance, area, or volume. It is argued that if the first sample unit is selected at a random location, then all successive units are random also.

By subdividing each block of work into a convenient large number of sub-blocks, using a random start, and following a systematic pattern, a random sample with uniform coverage of the block is obtained.

6.4.3 Selection of Sample Size

A statistically rational and valid method of selecting sample size is given in ASTM (Annual) Designation E-122, "Standard Recommended Practice for

Choice of Sample Size to Estimate the Average Quality of a Lot or Process." The equation for the number of units (sample size, n) to include in a sample in order to estimate, with a prescribed precision, the average of some characteristic of a lot is:

$$n = (t\sigma'/E)^2 \tag{6.10}$$

or, in terms of coefficient of variation

$$n = (tV'/e)^2 \tag{6.11}$$

where

- n = number of units in the sample
- t = a probability factor, from the Student-t Tables
- σ' = the known or estimated true value of the universe, or lot, standard deviation
- E = the maximum allowable error between the estimate to be made from the sample and the result of measuring (by the same methods) all the units in the lot
- V' = coefficient of variation = σ'/X , the known or estimated true value of the universe or lot
- e = E/X , the allowable sampling error expressed as a percent (or fraction) of X'
- X = the expected (mean) value of the characteristic being measured

6.5 Quality-Control Tests

Quality-control tests are performed on a scheduled basis by the inspection group in accordance with the systematic sampling technique selected and preferably in consonance with the construction group's work. Quality-control tests applicable to the construction of covers for uncontrolled waste sites are listed in Table 6-1. Tests are organized by geotechnical parameter. For most parameters, several test methods are given. The selection of a particular test method should be made on a site-specific basis, as each method has relative merits and limitations. However generally performed, and thus generally recommended, test methods are indicated by the footnote to Table 6.1. Descriptions of test methods are given in Appendix G.

6.6 Geomembrane/Geotextile Independent-Laboratory Verification Tests

Certain tests are performed by geomembrane/geotextile manufacturers to arrive at the specifications for their products. These same tests are sometimes also performed by the design group, should they not accept the manufacturer's claims for his product. The design group uses the test results to

TABLE 6-1

QUALITY-CONTROL TEST METHODS (SEE APPENDIX G)

Method	Number
Parameter Measured: Water Content	
Standard Oven-Dry[a]	1
Standard Nuclear Moisture/Density Gage[a]	2
Gas Burner	3
Alcohol Burning	4
Calcium Carbide (Speedy)	5
Microwave Oven	6
Infrared Oven	7
Parameter Measured: Unit Weight	
Standard Laboratory Volumetric	8
Standard Laboratory Displacement	9
Standard Field Sand-Cone	10
Standard Field Rubber Balloon	11
Standard Field Drive-Cylinder	12
Standard Nuclear Moisture/Density Gage	13
Parameter Measured: Specific Gravity	
Standard Laboratory	14
Parameter Measured: Grain-Size Distribution	
Standard Sieve Analysis (+200 Fraction)	15
Amount of Soil Finer than No. 200 Screen (Wash) Standard	16
Standard Laboratory Hydrometer ((-200 Fraction)	17
Pipette Method for Silt and Clay Fraction	18
Decantation Method for Silt and Clay Fraction	19
Parameter Measured: Liquid Limit	
Standard Multipoint[a]	20
Standard One Point	21
Parameter Measured: Plastic Limit	
Standard Laboratory[a]	22
Parameter Measured: Consistency (Cohesive Soil)	
Standard Unconfined Compression[a]	23
Field Expedient Unconfined Compression	24
Hand Penetrometer[a]	25
Handheld Torvane	26
Parameter Measured: Water Content/Density/Compactive Effort	
25 Blow Standard Proctor Compaction[a]	27
25 Blow Modified Proctor Compaction[a]	28
Nonstandardized Proctor Compaction[a]	29
Rapid, One Point Proctor Compaction	30
Rapid, Two Point Proctor Compaction[a]	31
Hilf's Rapid	32
Ohio Highway Department Rest of Curves	33
Harvard Miniature Compaction	34
Parameter Measured: Relative Density (Cohesionless Soil)	
Standard Laboratory Maximum Density[a]	35
Standard Laboratory Minimum Density[a]	36
Modified Providence	37
Parameter Measured: Geomembrane/Geotextile Seam Integrity	
Bonded Seam Strength[a]	38
Breaking Strength[a]	39
Peel Adhesion[a]	40
Air Lance	41
Vacuum Box[a]	42
Conductivity	43
Ultrasonic	44

[a]Generally recommended or preferred method.

decide on the geomembrane/geotextile to be specified in the design. The construction or inspection group, like the design group, performs these same tests. The construction or inspection group must perform these tests to assure that the product that arrives on site will in fact perform to the standard specified by the design. Normally neither the design group nor the construction/inspection group actually performs these tests itself. They contract an independent laboratory which has the requisite equipment to perform the tests. Thus although these tests can be considered quality-control tests, they are not performed by the inspection group. Thus they are not included in the previous section on test methods. However they will be merely identified here: ASTM designations D412 (tensile strength and elongation at failure) D2240 (hardness), D413 (seam strength), D624 using die C (tear strength), and Federal Test Method Standard 101B (puncture resistance).

6.7 Quality-Assurance Program

An effective quality-assurance program for the construction of covers for uncontrolled waste sites may take many forms. However any such program must have as its backbone complete documentation. Everything of importance to the quality-control system must be properly documented. This includes every observation, test, corrective action when a block of work is unacceptable, etc. The operative aspect of a quality-assurance program for the construction of covers for uncontrolled waste sites must be and is complete, proper documentation.

In the development of the Plan for remedial action at an uncontrolled hazardous-waste site, a Quality-Assurance program tailored to the particulars of the site and the planned action(s) should be formulated.

APPENDIX A

REFERENCES AND BIBLIOGRAPHY

ABC Dirt/Soil Scientists. 1981. Soil Properties, Classification, and Hydraulic Conductivity Testing. EPA/MERL Contract No. 68-03-2933, Seattle, WA, 128 pp.

Abdun-Nur, E. A. 1964. Discussion of "Significance of Test Results Obtained from Random Samples," by J. F. Shook, pp 13-30 in American Society for Testing and Materials (1964), q.v.

American Association of State Highway and Transportation Officials (published every four years). Standard Specifications for Transportation Materials and Methods of Sampling and Testing, AASHTO, Washington, DC, Two volumes: Part 1, Specifications; Part 2, Methods of Sampling and Testing.

American Society of Civil Engineers. 1949. Hydrology Handbook. Manual of Practice No. 28, ASCE, New York.

American Society of Civil Engineers. 1969. Design and Construction of Sanitary and Storm Sewers. Manuals and Reports on Engineering Practice, No. 37, ASCE, New York.

American Society for Testing and Materials (Annual). Annual Book of ASTM Standards, ASTM, Philadelphia, PA, Multiple volumes, including the following:

Part 15 - Road and Paving Materials; Bituminous and Polymeric Materials for Highway Construction, Waterproofing and Roofing, and Pipe; Traveled Surface Characteristics

Part 19 - Natural Building Stones: Soil and Rock

Part 35 - Plastics - General Test Methods, Nomenclature

Part 37 - Rubber, Natural and Synthetic - General Test Methods; Carbon Black

Part 38 - Rubber Products, Industrial - Specifications and Related Test Methods; Gaskets; Tires

American Society for Testing and Materials. 1959. Symposium on Application of Soil Testing in Highway Design and Construction. Special Technical Publication 239, ASTM, Philadelphia, PA, 127 pp.

American Society for Testing and Materials. 1964. Statistical Methods for Quality Control of Road and Paving Materials. Special Technical Publication 362, ASTM, Philadelphia, PA, 51 pp.

American Society for Testing and Materials. 1967. Permeability and Capillarity of Soils. Special Technical Publication 417, ASTM, Philadelphia, PA, 210 pp.

American Society for Testing and Materials. 1970. Special Procedures for Testing Soil and Rock for Engineering Purposes. Special Technical Publication 479, ASTM, Philadelphia, PA, 630 pp.

Anderson, A. G., Paintal, A. S., and Davenport, J. T. 1970. Tentative Design Procedure for Riprap-Lined Channels. NCHRP, Report 108, Highway Research Board, Washington, DC, 75 pp.

Anonymous. 1978. Climates of the States. Gale Research Co., Detroit, MI.

Antrim, J. D., et al. 1970. Rapid Test Methods for Field Control of Highway Construction. NCHRP Report 103, Highway Research Board, Washington, DC.

Arkin, H., and Colton, R. R. 1950. An Outline of Statistical Methods. 4th edition, Barnes and Noble Inc., New York.

Asphalt Institute. 1976. Asphalt in Hydraulics (Revised edition). Manual Series No. 12 (MS-12), The Asphalt Institute, College Park, MD, 68 pp.

Asphalt Institute. 1978. Asphalt Paving Manual. 3rd edition. Manual Series No. 8 (MS-8), The Asphalt Institute, College Park, MD.

Asphalt Institute. 1978. Soils Manual. Manual Series No. 10 (MS-10), March 1978 edition, The Asphalt Institute, College Park, MD, 238 pp.

Asphalt Institute. 1979. A Basic Asphalt Emulsion Manual. Manual Series No. 19 (MS-19), The Asphalt Institute, College Park, MD.

Atterberg, A. 1911. Uber die physikalische Bodenuntersuchung und über die Plastizität der Tone (On the Investigation of the Physical Properties of Soils and on the Plasticity of Clays). Internat. Mitteil. f. Bodenkunde, v. 1, pp 10-43.

August, H., Tatzky, R., Pastuska, G., and Win, T. 1984. Investigation of Permeability Behavior of Commercially Available Polymeric Membranes for Landfill Bottom Sealing in Contact with Leachate, Organic Solvents, and Their Aqueous Solutions. Research Report No. 103-02-208, Federal Environmental Agency, Berlin, West Germany, 108 pp.

Auvinet, G., and Espinosa, J. 1981. Impermeabilization of a 300-Hecture Cooling Pond, pp 151-167 in Zimmie and Riggs (1981), q.v.

Backstrom, J. E., Porter, L. C., Ore, E. L., and Wallace, G. B. 1974. Concrete in Construction. Appendix F, pp 645-665, in U. S. Bureau of Reclamation (1974a), q.v.

Bailey, R. G. 1978. Description of the Ecoregions of the United States, U. S. Department of Agriculture, Forest Service, Ogden, UT.

Baker, D. E. 1976. Soil Chemical Constraints in Tailoring Plants to Fit Problem Soils, in Wright (1976), q.v.

Barenberg, E. J. 1974. Utilization of Ash in Stabilized Base Construction, pp 180-196 in Faber, Echard, and Spencer (1974), q.v.

Bartos, M. J. 1977. Use of Dredged Material in Solid Waste Management. Technical Report D-77-11, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bell, J. R., Hicks, R. G., et al. 1980. Evaluation of Test Methods and Use Criteria for Geotechnical Fabrics in Highway Applications, FHWA/RD-80/021, Federal Highway Administration, Washington, DC, 191 pp.

Benjamin, J. R., and Cornell, C. A. 1970. Probability, Statistics, and Decision for Civil Engineers, McGraw-Hill Book Co., Inc., New York.

Bennett, F. W., and Donahue, R. L. 1975. Methods of Quickly Vegetating Soils of Low Productivity, EPA-440/9-75-006, U. S. Environmental Protection Agency, Washington, DC.

Bertrand, A. R. 1965. Rate of Water Intake in the Field, pp 197-209 in Black (1965), q.v.

Black, C. A. (editor-in-chief). 1965. Methods of Soil Analysis. Monograph 9 in the Series, "Agronomy," in two volumes: Part 1, Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling; Part 2, Chemical and Microbiological Properties, American Society of Agronomy, Inc., Madison, WI, 1572 pp.

Blaney, H. F. 1952. Definitions, Methods, and Research Data. Trans. Amer. Soc. Civil Engineers, v. 117, pp 949-973.

Blystone, J. R., Pelaner, A., and Steffens, G. P. 1961. Moisture Content Determination by the Calcium Carbide Gas Pressure Method, HRB Bull. 309, pp 77-84, Highway Research Board, Washington, DC.

Bohannon, J. R. 1978. Quality Assurance Engineering for Nuclear and Other Complex Facilities, Report No. TID-28368, Dept. of Nuclear Engineering, N. Carolina State University, Raleigh, NC.

Bouwer, H. 1978. Groundwater Hydrology. McGraw-Hill Book Company, Inc., New York, 480 pp.

Bradshaw, A. D., and Chadwick, M. J. 1980. The Restoration of Land: The Ecology and Reclamation of Derelict and Degraded Land. University of California Press, Berkeley and Los Angeles.

Bradshaw, A. D., Humphries, R. N., Johnson, M. S., and Roberts, R. D. 1977. The Restoration of Vegetation on Derelict Land Produced by Industrial Activity, in Holdgate and Woodman (1977), q.v.

Bradshaw, A. D., Marrs, R. H., Roberts, R. D., and Skeffington, R. A. 1982. The Creation of Nitrogen Cycles in Derelict Land, Phil. Trans. Roy. Soc. London, B 296: 557-561.

Brady, N. C. 1974. The Nature and Properties of Soils. 8th edition, Macmillan Co., New York, 639 pp.

Capp, J. P., and Spencer, J. D. 1970. Fly Ash Utilization, Applications, and Technology, Info. Circ. 8483, U. S. Bureau of Mines, Washington, DC, 72 pp.

Casagrande, A. 1932. The Structure of Clay and Its Importance in Foundation Engineering. Jour. Boston Soc. Civil Engineers, v. 19, no. 4, pp 168-221. Reprinted 1940 in "Contributions to Soil Mechanics," Boston Society of Civil Engineers.

Casagrande, A. 1948. Classification and Identification of Soils. Trans. Amer. Soc. Civil Engineers, v. 113, pp 901-991.

Cedergren, H. R. 1977. Seepage, Drainage, and Flow Nets. 2nd edition, John Wiley and Sons, Inc., New York, 534 pp.

Chow, V. T. 1964. Handbook of Applied Hydrology. McGraw-Hill Book Co., Inc., New York.

Chow, V. T. 1959. Open Channel Hydraulics. McGraw-Hill Book Co., Inc., New York.

Church, H. K. 1981. Excavation Handbook. McGraw-Hill Book Co., Inc., New York.

Clar, M. L., Das, P., Ferrandino, J., and Barfield, B. 1981. Handbook of Erosion and Sediment Control Measures for Coal Mines. Prepared by Hittman Associates, Inc., Columbia, MD, for Office of Surface Mining Reclamation and Enforcement, U. S. Department of the Interior.

Clayton, C. R. I., Simons, N. E., and Matthews, M. C. 1982. Site Investigation. Halsted Press (Wiley), New York, 424 pp.

Clements, F. E. 1920. Plant Indicators - The Relation of Plant Communities to Process and Practice. Publication 290, Carnegie Institution of Washington, Washington, DC.

Cline, J. F. 1979. Biobarriers Used in Shallow - Burial Ground Stabilization. PNL-2918, Battelle Pacific Northwest Laboratory, Richland, WA, 15 pp.

Collins, R. J., and Miller, R. H. 1976. Availability of Mining Wastes and Their Potential for Use as Highway Material. Vol I, Classification and Technical and Environmental Analysis, FHWA-RD-76-106, Federal Highway Administration, Washington, DC, 294 pp.

Collins, R. J. 1976a. Availability of Mining Wastes and Their Potential for Use as Highway Material. Vol II, Location of Mining and Metallurgical Wastes and Mining Industry Trends, FHWA-RD-76-107, Federal Highway Administration, Washington, DC, 129 pp.

Collins, R. J. 1976b. Availability of Mining Wastes and Their Potential for Use as Highway Material. Vol III, Annotated Bibliography, FHWA-RD-76-108, Federal Highway Administration, Washington, DC, 38 pp.

Collins, R. J., and Miller, R. H. 1977. Availability of Mining Wastes and Their Potential for Use as Highway Material - Executive Summary. FHWA-RD-78-28, Federal Highway Administration, Washington, DC, 40 pp.

Conway, R. A., and Malloy, B. C. (editors). 1981. Hazardous Solid Waste Testing: First Conference. ASTM Special Technical Publication 760, American Society for Testing and Materials, Philadelphia, PA, 386 pp.

Creager, W. P., Justin, J. D., and Hinds, J. 1946. Engineering for Dams. Vol III, John Wiley and Sons, Inc., New York.

Critchfield, H. J. 1974. General Climatology. 3rd edition, Prentice-Hall, Inc., Englewood Cliffs, NJ. 446 pp.

Daniels, F., and Alberty, R. A. 1961. Physical Chemistry. John Wiley and Sons, Inc., New York, 744 pp.

D'Appolonia, D. J. 1980. Soil-Bentonite Slurry Trench Cutoffs. Jour. Geotech. Eng. Div., ASCE, vol. 106, no. GT4, pp 399-417.

Davidson, D. T., et al. 1960. Methods for Testing Engineering Soils. Bull. No. 192, Engineering Experiment Station, Iowa State University, Ames, IA.

Davidson, G. R., et al. 1974. Bird/Aircraft Hazards. SW-116, U. S. Environmental Protection Agency, Washington, DC.

Davis, F. J. 1953. Quality Control of Earth Embankments. Proc. Third Intl. Conf. Soil Mechs. and Found. Engineering, Switzerland, Vol I, p 218.

Davis, S. N., and DeWiest, R. J. M. 1966. Hydrogeology. John Wiley and Sons, Inc., New York, 463 pp.

Dawson, J. F. 1950. Control of Damage by Muskrats to Earth Structures. Thesis. University of Saskatchewan.

Deming, W. E. 1950. Some Theory of Sampling. John Wiley and Sons, Inc., New York.

Department of the Army. 1970. Stability of Earth and Rock Fill Dams. Engineer Manual EM 1110-2-1902, Washington, DC.

Department of the Army. 1971. Bituminous Pavements---Standard Practice. TM 5-822-8, Washington, DC.

Department of the Army. 1972. Soil Sampling. Engineer Manual EM 1110-2-1907. Washington, DC.

Department of the Army. 1977. Construction Control for Earth and Rock-fill Dams. Engineer Manual EM 1110-2-1911, Washington, DC.

Department of the Army. 1978. Contracts - Quality Management. Appendix A, "Quality Control and Management," ER 1180-1-6, w/ch 1., Washington, DC.

Department of the Army. 1978. Design and Construction of Levees. Engineer Manual EM 1110-2-1913, Washington, DC.

Department of the Army. 1979. Geophysical Exploration. Engineer Manual EM 1110-1-1802, Washington, DC.

Department of the Army. 1980. Laboratory Soils Testing. Engineer Manual EM 1110-2-1906, Revised edition incorporating change 1, May 1980, Washington, DC.

Department of the Army. 1984. Geotechnical Investigations. Engineer Manual EM 1110-1-1804, Washington, DC.

Department of the Navy. 1971. Soil Mechanics, Foundations, and Earth Structures. NAVFAC DM-7, Alexandria, VA.

Department of the Navy. 1982. Soil Mechanics. NAVFAC DM-7.1, Washington, DC.

Departments of the Army and Air Force. 1979. Drainage and Erosion Control: Subsurface Drainage Facilities for Airfield Pavements. TM 5-820-2, AFM 88-5, Chap. 2, Washington, DC.

Departments of the Army and Air Force. 1982. Procedures for Foundation Design of Buildings and Other Structures (Except Hydraulic Structures). TM 5-818-1, AFM 88-3, Chap. 7, Washington, DC.

Departments of the Army, Air Force, and Navy. 1982. Soil Stabilization for Pavements. TM 5-822-4, AFM 88-7, Chap. 4, NAVFAC DM 21.5, Washington, DC.

DiGioia, A. M., Jr., and Muzzo, W. L. 1972. Fly Ash as Structural Fill. Jour. Power Div., ASCE, vol. 98, no. PO 1, pp 77-92.

Dobrin, M. B. 1976. Introduction to Geophysical Prospecting. McGraw-Hill Book Co. Inc., New York.

Dodge. 1980. See McMahon, 1979.

Enrick, N. L. 1972. Quality Control and Reliability. 6th edition, Industrial Press, Inc., New York.

Epstein, E. 1976. Genetic Potentials for Solving Problems of Soil Mineral Stress: Adaptation of Crops to Salinity, in Wright (1976), q.v.

93 1 29 041 223

Evans, R. B. 1982. Currently Available Geophysical Methods for Use in Hazardous Waste Site Investigations, pp 93-115 in Long and Schweitzer (1982), q.v.

Faber, J. H., Eckard, W. E., and Spencer, J. D. (compilers). 1974. Ash Utilization - Proceedings, Third International Ash Utilization Symposium, Pittsburgh, PA, March 1973, Info. Circ. 8640, U. S. Bureau of Mines, Washington, DC, 317 pp.

Farmer, W. J., Yang, M., Letey, J., and Spencer, W. F. 1976. Problems Associated with the Land Disposal of an Organic Industrial Hazardous Waste Containing HCB, pp 177-185 in Fuller (1976), q.v.

Farmer, W. J., Yang, M. S., Letey, J., and Spencer, W. F. 1980. Land Disposal of Hexachlorobenzene Wastes. EPA-600/2-80-119, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 69 pp.

Federal Aviation Agency. 1970. Airport Drainage. Advisory Circular A/C 150-5320-5B, FAA, U. S. Department of Transportation, Washington, DC.

Fenn, D. G., Hanley, K. J., and DeGeare, T. V. 1975. Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites. EPA/530/SW-168, U. S. Environmental Protection Agency, Cincinnati, OH, 40 pp.

Fouss, J. L. 1974. Drain Tube Materials and Installation. Chapter 8, pp 147-177, in Van Schilfgaarde (1974), q.v.

Foy, C. D., Voight, P. W., and Schwartz, J. W. 1980. Differential Tolerance of Weeping Lovegrass Genotypes to Acid Coal Mine Spoils. Agronomy Journal, 72: 859.

Fuller, W. H. (editor). 1976. Residual Management by Land Disposal; Proceedings of Hazardous Wastes Research Symposium. EPA-600/9-76-015, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 270 pp.

Geotechnical Laboratory. 1982. The Unified Soil Classification System. Tech. Memo. 3-357, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS, (reprint of report originally published 1960).

Gilluly, J., Waters, A. C., and Woodford, A. O. 1959. Principles of Geology. 2nd edition, W. H. Freeman and Co., San Francisco, 534 pp.

Graham, E. H. 1941. Legumes for Erosion Control and Wildlife. Misc. Pub. 412, U. S. Department of Agriculture, Washington, DC.

Gray, D. H. (chairman). 1977. Geotechnical Practice for Disposal of Solid Waste Materials. Proceedings, Specialty Conference, Geotech. Eng. Div., ASCE, at Ann Arbor, MI, June 1977, Amer. Soc. Civil Engineers, New York, NY, 885 pp.

Green, W. H., and Ampt, G. A. 1911. Studies on Soil Physics I. The Flow of Air and Water Through Soils. Jour. Agricultural Sci., Vol. 4, pp 1-24.

Gupta, S. C., et al. 1978. The Agricultural Value of Dredged Material. Tech. Report D-78-36, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hafenrichter, A. L., Schwendiman, J. L., Harris, H. L., MacLauchlan, R. S., and Miller, H. W. 1979. Grasses and Legumes for Soil Conservation in the Pacific Northwest and Great Basin States. Agriculture Handbook No. 339, Soil Conservation Service, U. S. Department of Agriculture, Washington, DC, 69 pp.

Hald, A. 1952. Statistical Theory with Engineering Applications. John Wiley and Sons, Inc., New York.

Harr, M. E. 1977. Mechanics of Particulate Media, a Probabilistic Approach. McGraw-Hill Book Co. Inc., New York.

Harris, D. H., and Chaney, F. B. 1969. Human Factors in Quality Assurance. John Wiley and Sons, Inc., New York.

Hart, Fred C., Associates, Inc. 1980. Kin-Buc Landfill Remedial Program. Project No. 2-8006-01, report to EPA, Region II, 24 pp.

Haxo, H. E. 1981. Testing Materials for Use in the Lining of Waste Disposal Facilities, pp 269-292 in Conway and Malloy (1981), q.v.

Haxo, H., Jr., Dakessian, S., Fong, M. A., and White, R. M. 1980. Lining of Waste Impoundment and Disposal Facilities. EPA/530/SW-870C, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 385 pp.

Haxo, H. E., Jr., et al. 1983. Lining of Waste Impoundment and Disposal Facilities. SW-870 (revised). Government Printing Office, Washington, DC. 055-00000231-2.

Heim, G. E., and Machalinski, M. V. 1980. Characterization of Existing Surface Conditions at Sheffield Low-Level Waste Disposal Facility. NUREG/CR-1683, U. S. Nuclear Regulatory Commission, Washington, DC, 88 pp.

Hilf, J. W. 1970. Rapid Compaction Control, pp 502-515 in American Society for Testing and Materials (1970), q.v.

Hilf, J. W. 1974a. Foundations and Construction Materials, Chapter V, pp 107-204, in U. S. Bureau of Reclamation (1974a), q.v.

Hilf, J. W. 1974b. Construction of Embankments. Appendix E, pp 619-644, in U. S. Bureau of Reclamation (1974a), q.v.

Hilf, J. W. 1974c. Soil Mechanics Nomenclature, Appendix D, pp 599-617, in U. S. Bureau of Reclamation (1974a), q.v.

Holdgate, M. N., and Woodman, M. J. (editors). 1977. The Breakdown and Restoration of Ecosystems. NATO Conference Series I, Ecology 3: 249-276, Plenum, New York.

Holtan, H. N. 1961. A Concept for Infiltration Estimates in Watershed Engineering. Agricultural Research Service, U. S. Department of Agriculture, Washington, DC.

Holtan, H. N., et al. 1975. USDAHA-74 Revised Model of Watershed Hydrology. Tech. Bull. 1518, Agricultural Research Service, U. S. Department of Agriculture, Washington, DC.

Horton, R. E. 1933. The Role of Infiltration in the Hydrologic Cycle. Trans. Amer. Geophys. Union, vol. 14, pp 446-460.

Horton, R. E. 1939. Analysis of Runoff-Plat Experiments with Varying Infiltration-Capacity. Trans. Amer. Geophys. Union, vol. 20, pp 693-711.

Horz, R. C. 1983. Applications of Geotextiles to Land Disposal Sites. Paper delivered at Ninth Annual Research Symposium, Land Disposal, Incineration and Treatment of Hazardous Wastes, Cincinnati, OH.

Hough, B. K. 1969. Basic Soils Engineering. 2nd edition, Ronald Press, New York.

Huggins, L. F., and Monke, E. S. 1970. Mathematical Simulation of Hydrologic Events on Ungaged Watersheds. Tech. Report no. 14, Department of Agriculture Engineering, Purdue University, W. Lafayette, IN.

Hveem, F. N. 1957. Maximum Density and Optimum Moisture of Soils. HRB Bull. 159, pp 1-21, Highway Research Board, Washington, DC.

Hvorslev, M. J. 1948. Subsurface Exploration and Sampling of Soils for Civil Engineering Purposes. Research report published by the Waterways Experiment Station, Corps of Engineers, U. S. Army, Vicksburg, MS; subsequently republished by the Engineering Foundation, New York, NY, 465 pp.

Hvorslev, M. J. 1949. Time Lag in the Observation of Ground-Water Levels and Pressures. U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Intergovernmental Methane Task Force. 1979. Methane from Landfills: Hazards and Opportunities; A Working Symposium. IMTF: EPA Region VIII, Colorado Department of Health, Tri-County District Health Department, and others, Denver, CO.

Israelsen, C. E., et al. 1980. Erosion Control During Highway Construction. NCHRP Report 221, Transportation Research Board, Washington, DC.

Johnson, A. I., and Kunkel, F. 1963. Some Research Related to Ground-Water Recharge - A Progress Report from the U. S. Geological Survey. Paper presented at Biennial Conference on Ground-Water Recharge and Ground-Water Basin Management, University of California, Berkeley, CA, 17 pp.

Johnson, A. I., and Richter, R. C. 1967. Selected Bibliography on Permeability and Capillarity Testing of Rock and Soil Materials, pp 176-210 in American Society for Testing and Materials (1967), q.v.

Johnson, A. I. 1981. Glossary, pp 3-17, in Zimmie and Riggs (1981), q.v.

Johnson, A. W., and Sallberg, J. R. 1960. Factors That Influence Field Compaction of Soils. HRB Bull. 272, Highway Research Board, Washington. DC.

Johnson, A. W., and Sallberg, J. R. 1962. Principal Methods for Determining Maximum Unit Weight and Optimum Moisture Content. JRB Bull. 319, Highway Research Board, Washington, DC.

Jones, A. K., et al. 1982. Coverings for Metal Contaminated Land. Proceedings, Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Washington, DC.

Jorgenson, J. L. 1969. Measuring the Variability of Compacted Embankments. HRB Record 290, pp 23-34, Highway Research Board, Washington, DC.

Joslin, J. G. 1959. Ohio's Typical Moisture-Density Curves, pp 111-118, in American Society for Testing and Materials (1959), q.v.

JRB Associates, Inc. 1982. Handbook for Remedial Action at Waste Disposal Sites. EPA-625/6-82-006, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 497 pp. Note: this handbook was reprinted as Rogoshewski, Bryson, and Wagner (1983), q.v.

Juran, J. M. (editor-in-chief). 1962. Quality Control Handbook. 2nd edition, McGraw-Hill Book Co., New York.

Karimi, A. A. 1983. Studies of the Emission and Control of Volatile Organics in Hazardous Waste Landfills. Unpublished Ph.D. dissertation, University of Southern California, Los Angeles.

Kay, B. L. 1976. Hydroseeding, Straw, and Chemicals for Erosion Control. Agronomy Progress Report No. 77, Department of Agronomy and Range Sciences, University of California, Davis, CA, 14 pp.

Kay, B. L. 1978. Mulches for Erosion Control and Plant Establishment on Disturbed Sites. Agronomy Progress Report No. 87, Agr. Exper. Station, University of California, Davis, CA, 19 pp.

Kay, B. L. 1979. Hydromulching Fibers - What's New? Agronomy Progress Report No. 98, Agr. Exper. Station, University of California, Davis, CA.

Kays, W. B. 1977. Construction of Linings for Reservoirs, Tanks and Pollution Control Facilities. Wiley Interscience, John Wiley and Sons, Inc., New York, 379 pp.

Kerr, K. W. (editor-in-chief). 1981. Cost Data for Landscape Construction. Kerr Associates, Inc., Minneapolis, MN, 244 pp.

Kirpich, Z. P. 1940. Time of Concentration of Small Agricultural Watersheds. Civil Engineering, v. 10, no. 6.

Krynine, D. P., and Judd, W. R. 1957. Principles of Engineering Geology and Geotechnics, McGraw-Hill Book Co. Inc., New York, 730 pp.

Lambe, T. W. 1951. Soil Testing for Engineers. John Wiley and Sons, Inc., New York.

Lambe, T. W., and Whitman, R. V. 1969. Soil Mechanics. John Wiley and Sons, Inc., New York, 553 pp.

Langfelder, L. J., and Nivargikar, V. R. 1967. Some Factors Influencing Shear Strength and Compressibility of Compacted Soils. HRB Record 177. Highway Research Board, Washington, DC.

Lanz, L. J. 1968. Dimensional Analysis Comparison of Measurements Obtained in Clay with Torsional Shear Instruments. M.S. Thesis, Mississippi State University, Starkville, MS.

Lee, C. R., Skogerboe, J. G., Eskew, K., Price, R. W., Page, N. R., Clar, M., Kort, R., and Hopkins, H. 1984. Restoration of Problem Soil Materials at Corps of Engineers Construction Sites. Instruction Report EL-84-1, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., et al. 1976. Feasibility of the Functional Use of Vegetation to Filter, Dewater, and Remove Contaminants from Dredged Material. Tech. Report D-76-4, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Leonards, G. A., editor. 1962. Foundation Engineering. McGraw-Hill Book Co. Inc., New York, 1136 pp.

Leone, I. A., et al. 1979. Adapting Woody Species and Planting Techniques to Landfill Conditions. EPA-600/2-79-128, U. S. Environmental Protection Agency, Cincinnati, OH.

Lester, R. H., Enrick, N. L., and Mottley, H. E. 1977. Quality Control for Profit. Industrial Press, Inc., New York.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H. 1958. Hydrology for Engineers. McGraw-Hill Book Co. Inc., New York.

Linsley, R. K., and Franzini, J. B. 1979. Water Resources Engineering 3rd edition, McGraw-Hill Book Co. Inc., New York.

9 3 1 2 9 0 4 1 2 2 8

Lull, H. W. 1953. Evapotranspiration: Excerpts from Selected References. Occas. Paper 131, Southern Forest Experiment Station, Forest Service, U. S. Department of Agriculture, New Orleans, LA.

Lutton, R. J. 1980. Evaluating Cover Systems for Solid and Hazardous Waste. SW-867, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 57 pp.

Lutton, R. J., Regan, G. L., and Jones, L. W. 1979. Design and Construction of Covers for Solid Waste Landfills. EPA-600/2-79-165, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 250 pp.

Lutton, R. J., et al. 1982. Parameters for Characterizing Sites for Disposal of Low-Level Radioactive Waste. NUREG/CR-2700, U. S. Nuclear Regulatory Commission, Washington, DC.

Martin. 1978. See Tolman et al., 1978.

Martin, A. C., Zim, H. S., and Nelson, A. L. 1951. American Wildlife and Plants. McGraw-Hill Book Co., Inc., New York.

Martin, J. P., Koerner, R. M., and Whitty, J. E. 1984. Experimental Friction Evaluation of Slippage Between Geomembranes, Geotextiles, and Soils. Proceedings, Intl. Conf. on Geomembranes, Denver, CO., June 1984, vol 1, pp 191-196.

McDowell, C. 1972. Flexible Pavement Design Guide. Bull. 327, National Lime Association.

McKell, C. M. 1975. Shrubs - A Neglected Resource of Arid Lands. Science, 187: 803-809.

McMahon, L. A. (editor). 1979. 1980 Dodge Guide to Public Works and Heavy Construction Costs. (Published annually), McGraw-Hill Publ. Co., New York, 221 pp.

Means, Robert S., Company. 1980. Building Construction Cost Data 1980. (Published annually), RSM Co., Kingston, MA, 371 pp.

Meyer, M. P., and Knight, S. J. 1961. Trafficability of Soils - Soil Classification. Tech. Memo. 3-240, Supplement 16, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Middlebrooks, E. J., Jones, N. B., Reynolds, J. H., Torpy, M. F., and Bishop, R. P. 1978. Lagoon Information Source Book. Ann Arbor Science Publishers, Ann Arbor, MI, 215 pp.

Miller, D. E., and Bunger, W. C. 1963. Moisture Retention by Soil with Coarse Layers in the Profile. Soil Sci. Soc. Amer. Proceedings, vol 27, no. 5, pp 586-589.

Miller, I., and Freund, J. E. 1977. Probability and Statistics for Engineers. 2nd edition, Prentice-Hall, Englewood Cliffs, NJ, 529 pp.

Miller-Wardon Associates. 1965. Development of Guidelines for Practical and Realistic Construction Specifications. NCHRP Report 17, Highway Research Board, Washington, DC.

Mills, W. H. 1970. Grain Size Analysis of Soil by Elutriation, pp 88-90, in American Society for Testing and Materials (1970), q.v.

Mitchell, J. K. 1976. Fundamentals of Soil Behavior. John Wiley and Sons, Inc., New York, 422 pp.

Moore, C. A. 1980. Landfill and Surface Impoundment Performance Evaluation. EPA/SW-869, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH.

Mueller-Dombois, D., and Ellenberg, H. 1974. Aims and Methods of Vegetation Ecology. John Wiley and Sons, Inc., New York.

National Cooperative Highway Research Program. 1979. Quality Assurance. NCHRP Synthesis 65, Transportation Research Board, Washington, DC, 42 pp.

National Oceanic and Atmospheric Administration. 1974. Climatic Atlas of the United States. NOAA, U. S. Department of Commerce, Washington, DC (see Table 2.1, this handbook).

Nevada State Conservation Commission. (No date). Handbook of Best Management Practices, Non-designated Area Water Quality Management Plan, Loose-leaf notebook, Carson City, NV.

Neville, A. M., and Kennedy, J. B. 1964. Basic Statistical Methods for Engineers and Scientists. International Textbook Co., Scranton, PA.

Nichols, H. L., Jr. 1962. Moving the Earth: The Workbook of Excavation, 2nd edition, North Castle Books, Greenwich, CT.

Nolan, M. E., Hatano, M. M., Howell, R. B., and Shirley, E. C. 1976. Control of Ditch Erosion Using Fiberglass Roving. California Department of Transportation, Sacramento, 26 pp.

Nolan, M. E., Spring, R. J., and Howell, R. B. 1978. Control of Slope Erosion Using Fiberglass Roving with Vegetation. California Department of Transportation, Sacramento, 92 pp.

Oglesby, C. H. 1975. Highway Engineering. 3rd edition, John Wiley and Sons, Inc., New York, 783 pp.

Olson, R. E., and Daniel, D. E. 1981. Measurement of the Hydraulic Conductivity of Fine-Grained Soils, pp 18-64 in Zimmie and Riggs (1981), q.v.

Overton, D. C. 1964. Mathematical Refinement of an Infiltration Equation for Watershed Engineering. Agricultural Research Service, U. S. Department of Agriculture, Washington, DC.

Parcher, J. V., and Means, R. E. 1968. Soil Mechanics and Foundations. Merrill Co., Columbus, OH.

Parker, D. G., Thornton, S. I., and Cheng, C. W. 1977. Permeability of Fly Ash Stabilized Soils, pp 63-71 in Gray (1977), q.v.

Parry, G. D. R., Bell, R. M., and Jones, A. K. 1982. Degraded and Contaminated Land Reuse - Covering Systems, in Proceedings, National Conference on Management of Uncontrolled Hazardous Waste Sites, Washington, DC.

Peck, R. B., Hanson, W. E., and Thornburn, T. H. 1974. Foundation Engineering. 2nd edition, John Wiley and Sons, Inc., New York, 514 pp.

Price, J. T. 1978. Soil Compaction Specification Procedure for Desired Field Strength Response. Report No. 78-7, Joint Highway Research Project, Purdue University, W. Lafayette, IN.

Proctor, R. R. 1933. Four Articles on the Design and Construction of Rolled-Earth Dams. Engineering News-Record, vol. III, pp 245-248, 286-289, 348-351, 372-376.

Rankin, W. L. 1970. Organic Matter Content of Soils by Redox Titration, pp 286-287 in American Society for Testing and Materials (1970), q.v.

Redus, J. F., and Spigolon, S. J. 1965. Model Specifications for Embankment and Base Course Construction II. Proceedings, Highway Conference on Research and Development of Quality Control and Acceptance Specifications, Vol. 1, pp 459-476, U. S. Bureau of Public Roads, Washington, DC.

Ree, W. O., and Palmer, V. J. 1949. Flow of Water in Channels Protected by Vegetative Linings. Tech. Bull. 967, Soil Conservation Service, U. S. Department of Agriculture, Washington, DC, 115 pp.

Richards, L. A. (editor). 1969. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60, Science and Education Administration, U. S. Department of Agriculture, Riverside, CA.

Richards, L. A., and Middleton, L. M. 1978. Best Management Practices for Erosion and Sediment Control. FHWA-HD-15-1, Federal Highway Administration, Region 15, Arlington, VA.

Rishel, H. L., Boston, T. M., and Schmidt, C. J. 1981. Costs of Remedial Response Actions at Hazardous Waste Sites. Revised final report EPA-600/2-82-035, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH, 144 pp. Also published by Noyes Data Corp. (1984) as "Costs of Remedial Response Actions at Uncontrolled Hazardous Waste Sites".

Ritchie, J. T. 1972. A Model for Predicting Evaporation from a Row Crop with Incomplete Cover. Water Resources Research, vol. 8, no. 5, pp 1204-1213.

Rogoshewski, P., Bryson, H., and Wagner, K. 1983. Remedial Action Technology for Waste Disposal Sites. Noyes Data Corp., Park Ridge, NJ. 500 pp. (Reprinted from JRB Associates, 1982; q.v.)

Rovers, F. A., Tremblay, J. J., and Mooij, H. 1977. Procedures for Landfill Gas Monitoring and Control. EPS 4-EC-77-4, Waste Management Branch, Environment Canada, Ottawa.

Schaake, J. C., Jr., Geyer, J. C., and Knapp, J. W. 1967. Experimental Analysis of the Rational Method. Jour. Hyd. Div., ASCE, vol. 93, no. HY6.

Schlegel Lining Technology, Inc. 1983. Quality Control Program for Installation of Schlegel Sheet High Density Polyethylene. The Woodlands, TX.

Schmidt, N. O. 1970. Organic Carbon Content of Soil by Wet Combustion, pp 271-278 in American Society for Testing and Materials (1970), q.v.

Schmugge, T. J., Jackson, T. J., and McKim, H. L. 1980. Survey of Methods for Soil Moisture Determination. Water Resources Research, vol. 16, no. 6, p 961-979.

Schomaker, N. B., and Murdock, R. F. 1969. Selection and Placement of Soil Cover Material in a Sanitary Landfill. Open File Report UD-03-68-20, U. S. Public Health Service, Cincinnati, OH.

Schroeder, P. R., Gibson, A. C., and Smolen, M. D. 1984. The Hydrologic Evaluation of Landfill Performance (HELP) Model; Vol. II, Documentation for Version I. EPA/530-SW-84-010, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH.

Schroeder, P. R., Morgan, J. M., Walski, T. M., and Gibson, A. C. 1984. The Hydrologic Evaluation of Landfill Performance (HELP) Model; Vol. I, User's Guide for Version I. EPA/530-SW-84-009, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH.

Schwab, G. O., Frevert, R. K., Edminster, T. W., and Barnes, K. K. 1981. Soil and Water Conservation Engineering. Third edition, John Wiley and Sons, New York, 525 pp.

Schwartz, A. E. 1967. Rapid Means of Determining Density and Moisture Content of Soils and Granular Materials. Bull. 109, Engineering Experiment Station, Clemson University, Clemson, SC.

SCS Engineers. 1980. Surface Impoundment Assessment in California. Report prepared under contract no. 68-01-5137, to U. S. Environmental Protection Agency, SCS Engineers, Long Beach, CA, 235 pp.

SCS Engineers. 1981. Remedial Actions at Hazardous Waste Sites: Survey and Case Studies. Report prepared under contract no. 68-01-4885, to U. S. Environmental Protection Agency, SCS Engineers, Long Beach, CA, 230 pp.

Shafer, R.A., Renta-Babb, A., Bandy, J. T., Smith, E. D., and Malone, P. G. 1984. Landfill Gas Control at Military Installations. CERL-TR-N-173, U. S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, IL.

Shaw, M. D., and Arble, W. C. 1959. Bibliography on Methods for Determining Soil Moisture. Engineering Research Bull. B-78, Pennsylvania State University, State College, PA.

Sherard, J. L., and Decker, R. S. (editors). 1977. Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects. ASTM Spec. Tech. Pub. 623, American Society for Testing and Materials, Philadelphia, PA, 486 pp.

Sherard, J. L., Dunnigan, L. P., and Decker, R. S. 1976. Identification and Nature of Dispersive Soils. Jour. Geotech. Eng. Div., ASCE, vol. GT4, pp 287-301.

Sherard, J. L., Woodward, R. J., Gizienski, S. F., and Clevenger, W. A. 1963. Earth and Earth-Rock Dams. John Wiley and Sons, Inc., New York, 725 pp.

Sibley, E. A., and Yamane, G. 1965. A Simple Shear Test for Saturated Cohesive Soil. Proceedings, 5th Pacific Area National Meeting, ASTM, Seattle, WA.

Sisk, S. W. 1981. NEIC Manual for Groundwater/Subsurface Investigations at Hazardous Waste Sites. EPA-330/9-81-002, National Enforcement Investigation Center, U. S. Environmental Protection Agency, Denver, CO, 72 pp plus appendices.

Smith, P. C. 1970. Rapid Determination of Approximate Moisture Content of Soils for Field Control of Embankment Construction, pp 447-459 in American Society for Testing and Materials (1970), q.v.

Smith, R. A. H., and Bradshaw, A. D. 1972. Stabilization of Toxic Mine Wastes by the Use of Tolerant Plant Populations. Trans. Inst. Min. Metall., 81A: 230-237.

Snethen, D. R., Johnson, L. D., and Patrick, D. M. 1977a. An Investigation of the Natural Microscale Mechanisms that Cause Volume Change in Expansive Clays. FHWA-RD-77-75, Federal Highway Administration, Washington, DC, 285 pp.

Snethen, D. R., Johnson, L. D., and Patrick, D. M. 1977b. An Evaluation of Expedient Methodology for Identification of Potentially Expansive Soils. FHWA-RD-77-94, Federal Highway Administration, Washington, DC, 43 pp.

Soil Conservation Service. 1973. Typical Specifications for Construction of Earth-fill Dams. Southern Region, SCS, U. S. Department of Agriculture.

Soil Conservation Service. 1974. Hydrology. Section 4, National Engineering Handbook, SCS, U. S. Department of Agriculture, Washington, DC.

Sowers, G. B., and Sowers, G. F. 1970. Soil Mechanics and Foundations. 3rd edition, Macmillan Co., New York.

Spaine, P. A., Llopsis, J. L., and Perrier, E. R. 1978. Guidance for Land Improvement Using Dredged Material. Tech. Report DS-78-21, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Spangler, M. G., and Handy, R. L. 1982. Soil Engineering. 4th edition, Harper and Row, New York.

Spigolon, S. J., and Kelley, M. F. 1984. Geotechnical Quality Assurance of Construction of Disposal Facilities. EPA-600/2-84-040, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, Cincinnati, OH.

Spooner, P. A., Wetzel, R. S., Spooner, C. E., Furman, C. A., Tokarski, E. F., Hunt, G. E., Hodge, V., and Robinson, T. 1984. Slurry Trench Construction for Pollution Migration Control. EPA-540/2-84-001, U. S. Environmental Protection Agency, Washington, DC, and Cincinnati, OH., approx. 240 pp.

Stephenson, L. M. 1970. Construction Quality Assurance. USAE South Atlantic Division, Washington.

Strohm, W. E., and Torrey, V. H. 1982. Analysis of Field Compaction Data, DeGray Dam, Caddo River, Arkansas, Misc. Paper GL-82-4, U. S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Taylor, D. W. 1948. Fundamentals of Soil Mechanics. John Wiley and Sons, Inc., New York, 700 pp.

Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A. 1976. Applied Geophysics. Cambridge University Press, New York.

Teng, W. C. 1962. Foundation Design. Prentice-Hall, Englewood Cliffs, NJ, 466 pp.

Terzaghi, K., and Peck, R. B. 1967. Soil Mechanics in Engineering Practice. 2nd edition, John Wiley and Sons, Inc., New York, 729 pp.

Thompson, M. M. 1979. Maps for America. U. S. Geological Survey, U. S. Government Printing Office, Washington, DC, 265 pp.

Thornburg, A. A. 1979. Plant Materials for Use on Surface Mined Lands. TP-157 and EPA-600/7-79-134, Soil Conservation Service, U. S. Department of Agriculture, Washington, DC.

Thornthwaite, C. W., et al. 1944. Report of the Committee on Transpiration and Evaporation, 1943-44. Tran. Amer. Geophys. Union, vol. 25, part V, pp 683-693.

Thornthwaite, C. W., and Mather, J. R. 1955. The Water Balance. Publications in Climatology, vol. 8, no. 1, Drexel Institute of Technology, Centerton, NJ, 104 pp.

Thornthwaite, C. W., and Mather, J. R. 1957. Instruction and Tables for Computing Potential Evapotranspiration and the Water Balance. Publication in Climatology, vol. 10, no. 3, pp 185-311, Drexel Institute of Technology, Centerton, NJ.

Todd, D. K. 1970. The Water Encyclopedia. Water Information Center, Port Washington, NY.

Tolman, A. L., Ballestero, A. P., Jr., Beck, W. W., Jr., and Emrich, G. H. 1978. Guidance Manual for Minimizing Pollution from Waste Disposal Sites. EPA-600/2-78-142, U. S. Environmental Protection Agency, Cincinnati, OH, 95 pp.

Tomlinson, M. J. 1969. Foundation Design and Construction. 2nd edition, Pitman, London.

Turnbull, W. J., Compton, J. R., and Ahlvin, R. G. 1966. Quality Control of Compacted Earthwork. Jour. Soil Mech. Found. Div., ASCE, vol. 92, no. SM 1.

U. S. Army Engineer Waterways Experiment Station. 1954. A Study of Moisture Content Determinations on Selected Soils. Misc. Paper H-73, Vicksburg, MS.

U. S. Atomic Energy Commission. 1969. Quality Assurance Criteria for Nuclear Power Plants. 10 CFR 50, Appendix B, Washington, DC.

U. S. Bureau of Reclamation. 1974a. Design of Small Dams. 2nd edition, U. S. Government Printing Office, Washington, DC, 816 pp.

U. S. Bureau of Reclamation. 1974b. Earth Manual. 2nd edition, U. S. Government Printing Office, Washington, DC, 810 pp.

U. S. Department of Agriculture. 1937. Range Plant Handbook. Forest Service, U. S. Department of Agriculture, Washington, DC.

U. S. Department of Agriculture. 1972. Landscape for Living: Yearbook of Agriculture. Washington, DC.

U. S. Department of Agriculture. 1973. Seeding Non-Irrigated Lands in New Mexico. Range Technical Note 60, Soil Conservation Service, Science and Education Administration, Las Cruces, NM.

U. S. Department of Agriculture, Forest Service. 1979. User Guide to Soils; Mining and Reclamation in the West. Gen. Tech. Report INT-68, SEAM, Intermountain Forest and Range Experimental Station, Ogden, UT.

U. S. Department of Agriculture, Soil Conservation Service. 1975. Maryland Standards and Specifications for Soil Erosion and Sediment Control in Developing Areas. College Park, Md.

U. S. Department of Defense. (No date). Natural Resources - Land Management. Army TM 5-630, Washington, DC.

U. S. Environmental Protection Agency. 1976. Erosion and Sediment Control; Surface Mining in the Eastern United States, Planning. Vols. 1 and 2, EPA-625/3-76-006, U. S. Environmental Protection Agency, Washington, DC.

U. S. Environmental Protection Agency. 1982. Hazardous Waste Management System; Permitting Requirements for Land Disposal Facilities. Part II. Federal Register, vol. 47, no. 143, pp 32274-32388, Washington, DC.

U. S. Nuclear Regulatory Commission. 1982. Final Low-Level Waste Regulations. 10 CFR 61, Sec. 61.12, pp 94-96, Washington, DC.

U. S. Weather Bureau. 1955. Rainfall Intensity-Duration Curves. Tech. Paper 25, USWB, Washington, DC.

Van Schilfgaarde, J. (editor). 1974. Drainage for Agriculture. Monograph 17 in the Series, "Agronomy." American Society of Agronomy, Inc., Madison, WI, 700 pp.

Vieira, S. R., Nielsen, D. R., and Biggar, J. W. 1981. Spatial Variability of Field-Measured Infiltration Rate. Sci. Soc. Amer. Jour., vol. 45, pp 1040-1048.

Viessman, W., Jr., Knapp, J. W., Lewis, G. L., and Harbaugh, T. E. 1977. Introduction to Hydrology. 2nd edition, Harper and Row, New York.

Virginia Soil and Water Conservation Commission. 1980. Virginia Erosion and Sediment Control Handbook, 2nd ed., Richmond, VA.

Visher, S. S. 1954. Climatic Atlas of the United States. Harvard University Press, Cambridge, MA, 403 pp.

Whitman, R. V. 1960. Some Considerations and Data Regarding the Shear Strength of Clays. Research Conference on Shear Strength of Cohesive Soils, ASCE, Boulder, CO, pp 581-614.

Willardson, L. S. 1974. Envelope Materials. Chapter 9, pp 179-196, in Van Schilfgaarde (1974), q.v.

Willenbrock, J. H. 1976. A Manual for Statistical Quality Control of Highway Construction. Vols. 1 and 2, Purchase Order No. 5-1-3356, Federal Highway Administration, Washington, DC.

Willenbrock, J. H., and Shepard, S. 1980. Construction QA/QC Systems: Comparative Analysis. Jour. Construc. Div. ASCE, vol. 196, no. CO3, pp 371-387.

Wilson, S. D. 1970. Moisture-Density Relationships of Soil Using Harvard Compaction Apparatus, pp 101-103 in American Society for Testing and Materials (1970), q.v.

Winterkorn, H. F., and Fang, H. Y. 1975. Foundation Engineering Handbook. Van Nostrand Reinhold Co.

Woods, K. B., and Litehiser, R. R. 1938. Soil Mechanics Applied to Highway Engineering in Ohio. Bull. 99, Engineering Experiment Station, Ohio State University, Columbus.

Woods, K. B., Miles, R. D., and Lovell, C. W., Jr. 1962. Origin, Formation, and Distribution of Soils in North America. Chapter 1, pp 1-65, in Leonards (1962), q.v.

Wright, M. J. (editor). 1976. Plant Adaptation to Mineral Stress in Problem Soils. Cornell University Agricultural Experiment Station, Ithaca, NY.

Zimmie, T. F., and Riggs, C. O. (editors). 1981. Permeability and Groundwater Contaminant Transport. ASTM Spec. Tech. Pub. 746, American Society for Testing and Materials, Philadelphia, PA, 251 pp.

APPENDIX B

CASE HISTORIES

Case histories can convey valuable information to the cover designer, as they record actual experience, including problems that arise and their solution. Unfortunately to date not many cover systems have been designed and built at uncontrolled hazardous waste sites.

Two cases of recently installed cover systems at hazardous waste sites whose details were available to the preparers of this Handbook are presented here. These are the Sylvester hazardous waste site, near Nashua, NH, and the Kin-Buc sanitary landfill, in Edison Township, Middlesex County, NJ.

The cover designer wishing to investigate performance histories of established waste-site covers may consult documentation of low-level nuclear waste repositories, of which there are approximately a half dozen in the U. S., and of closed municipal landfills, of which there are many. Experience from such sites will be relevant in varying degrees for uncontrolled hazardous waste sites, since, particularly at municipal waste sites, covers have been called upon to perform various functions other than acting as an impermeable roof. Demonstrated problems at such sites have included, prominently, subsidence due to collapse of buried containers and erosion due to a variety of specific causes.

B.1 Sylvester Hazardous Waste Site

The Sylvester hazardous waste site, about 20 acres in size, is located on Gilson Road about three miles west of Nashua, NH. The New Hampshire Water Supply and Pollution Control Commission, pursuant to a cooperative agreement with the USEPA, contracted for site investigations and for remedial-action design and construction. The latter was carried out during the summer and fall of 1982.

Extensive site investigations including ground-water sampling, pumping tests, surface-water sampling, water-quality analyses, borings, test pits, and magnetometer surveys were performed. The presence of high levels of tetrahydrofuran, methylene chloride, and toluene, as well as other volatile organic compounds, was established. It was known that demolition debris, including stumps and timbers, had been buried at the site along with hazardous wastes. Over 1300 drums were removed from the site, but others were believed likely to be still buried.

The local geology comprises glacial sands, silts, and gravels, overlying schist bedrock at depths of about 30 to 100 ft. Impervious soils are rare in the area. Mean monthly temperatures range between 22°F (January) and 70°F (July); mean annual precipitation approximates 40 inches.

A bentonite-slurry trench (wall) was installed to bedrock completely enclosing the site. Site topography was modified by leveling several small prominences. The wastes were covered with a minimum thickness of 3 ft of local soil placed in 6-in. lifts and compacted with vibratory rollers to at least 95 pct of Standard Proctor maximum density. On the compacted surface was laid a 40-mil HDPE geomembrane. The roll width of the membrane was 22.5 ft, and adjoining strips were heat-bonded with lap joints. The membrane material showed approximately 500 pct elongation before failure. The membrane was laid over the top of the slurry wall and anchored with a V-shaped anchor trench around the periphery. The membrane was then covered with 3 ft of local soil, moderately compacted. Upon this was laid a 4-in. layer of "loam" or topsoil, which was seeded with a specified mixture of grasses and legumes.

Where exploration had indicated the maximum concentrations of decayable buried material, gas vents were installed, consisting of vertical PVC pipes perforated beneath the membrane, protruding 3 ft above final grade, and capped with activated-carbon gas adsorbers. Design details of these and other features are shown in Figures B-1-B-4, and views of the site during construction are shown in Figures B-5-B-7. Shafts for the gas-vent pipes were drilled with an auger through holes cut in the membrane; the joint between pipe and membrane was sealed with a flange connection as shown in Figure B-4. It was necessary in some places to stabilize the top of the slurry wall by laying a geotextile over it. A view of the geotextile, a nonwoven polyester, can be seen in Figure B-7.

The final grading plan called for cut slopes along the site boundaries as steep as 52 pct in places, and slopes over the cover of 3 to about 11 pct. A separate mix of grasses and legumes was specified for sloping areas. Around most of the perimeter a 15-20 ft wide flat was placed just outside the slurry wall. This can be driven on by vehicles. Also, being slightly canted outward toward the cut slopes, it acts as a de facto ditch, intercepting surface runoff from the slopes.

In the first few months since cover completion, the system has performed well for the most part but has experienced some erosion problems in swales from runoff when the soil above the membrane was saturated (Tom Roy, MHWSPCC, personal communication, 21 April 1983). Also there have been some erosion problems where subsurface water exits at the edge of the membrane.

A tabulation of the bid figures for remedial construction at the Sylvester site is presented in Table B-1.

FIGURE B-1

CAP DETAIL, SYLVESTER SITE (N.T.S.)

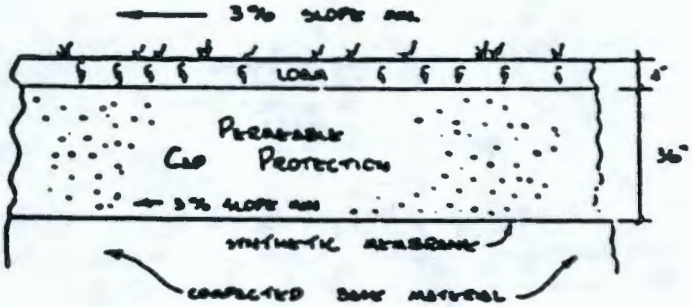
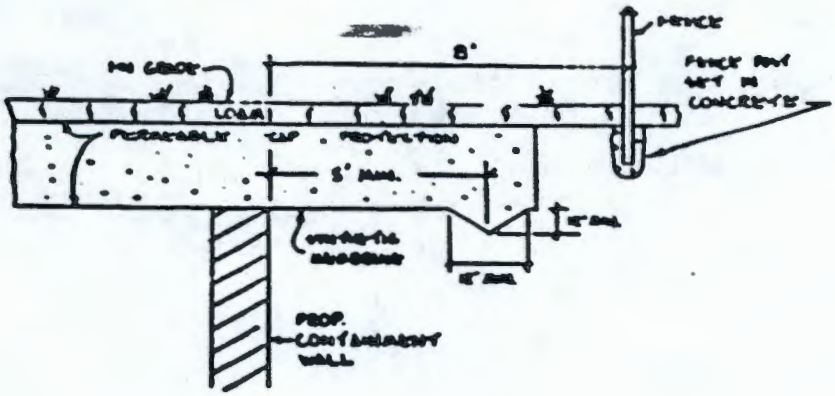


FIGURE B-2

DETAIL OF MEMBRANE CAP AT SLURRY WALL, SYLVESTER SITE (N.T.S.)



9 3 1 2 9 0 4 1 2 4 0

FIGURE B-3

GAS VENT DETAIL, SYLVESTER SITE (N.T.S.)

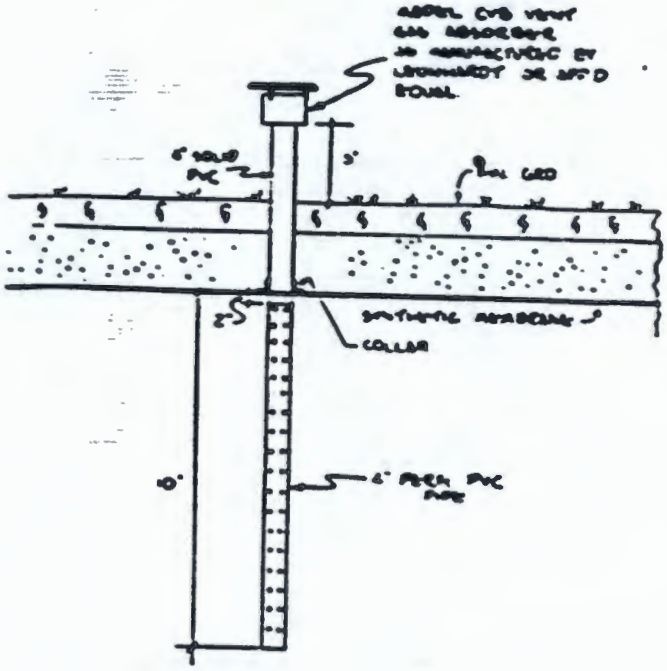


FIGURE B-4

DETAIL OF SEAL OF MEMBRANE CAP AROUND PIPE (N.T.S.)

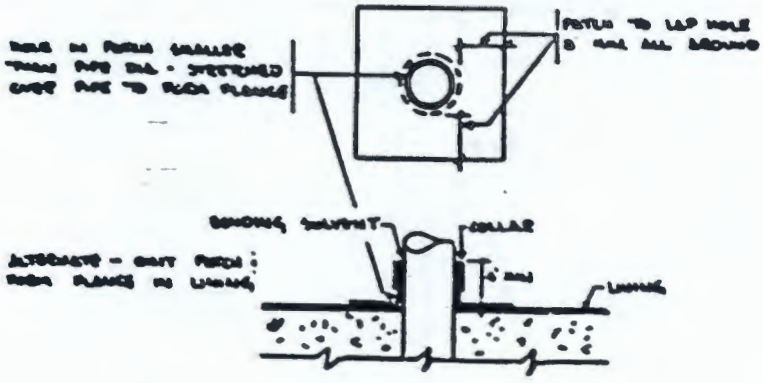


FIGURE B-5

GEOMEMBRANE BEING LAID AT SYLVESTER HAZARDOUS WASTE SITE, STRIP WIDTH IS 22.5 FEET, THICKNESS 40 MILS, MATERIAL HDPE. NOTE LAPPED SEAM AT RIGHT.

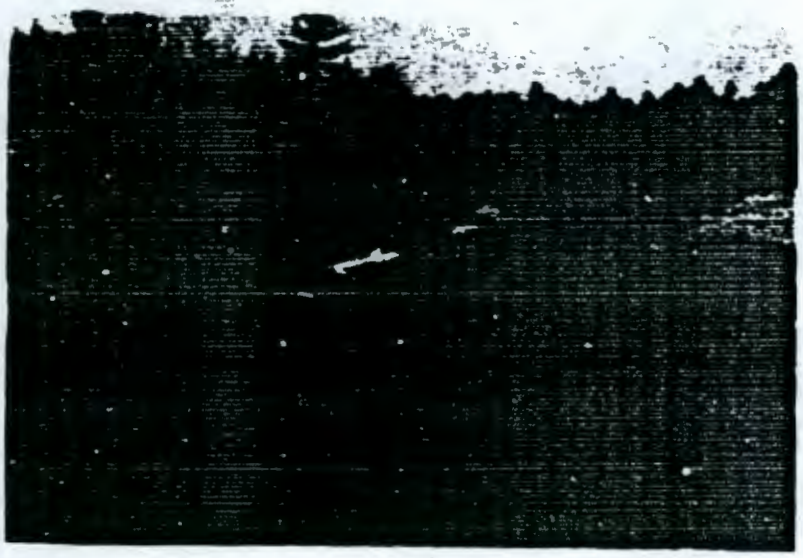
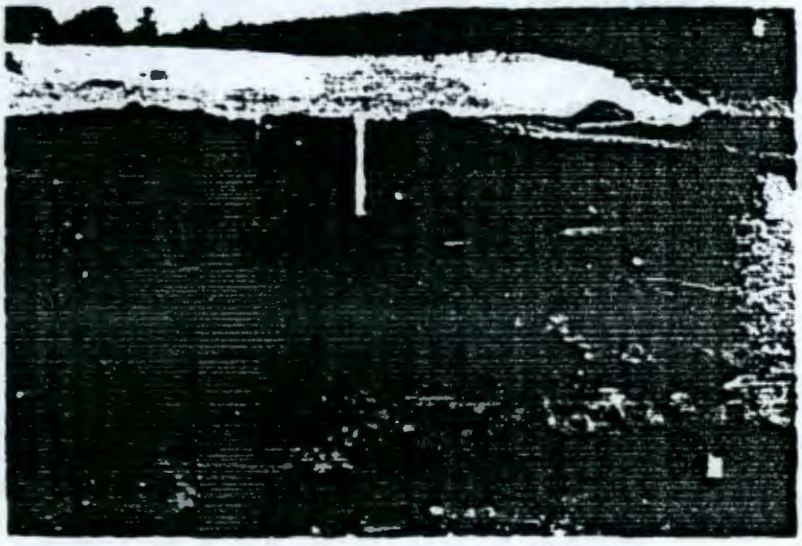


FIGURE B-6

GAS VENT PIPES PROTRUDING THROUGH 3-FT-THICK LAYER OF SOIL PLACED OVER GEOMEMBRANE, SYLVESTER HAZARDOUS WASTE SITE



9 3 1 2 9 0 4 1 2 4 2

FIGURE B-7

GEOTEXTILE LAID OVER SLURRY WALL FOR REINFORCEMENT. GEOMEMBRANE WILL BE LAID OVER GEOTEXTILE. BROOK, MIDDLE DISTANCE, RECEIVES LOCAL SURFACE DRAINAGE.

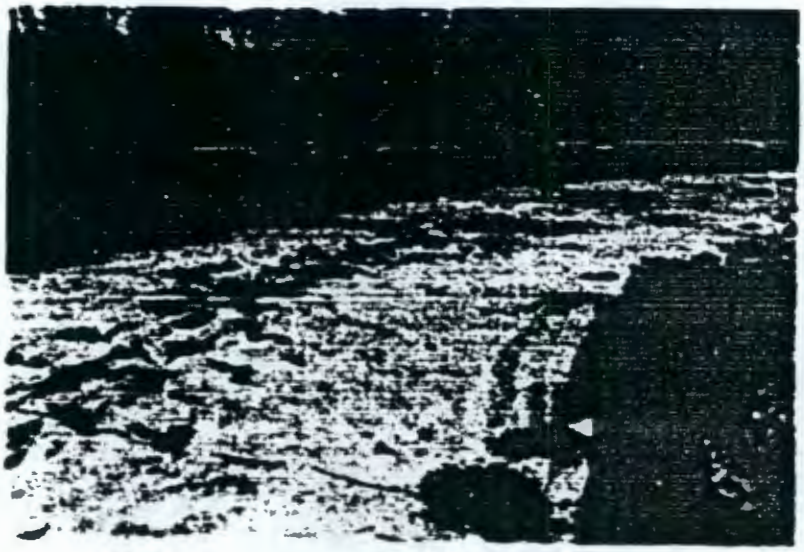


TABLE B-1

BID TABULATION FOR CAP AND CONTAINMENT WALL CONSTRUCTION AT THE SYLVESTER SITE, NASHUA, NEW HAMPSHIRE (SLURRY TRENCH METHOD)

Prepared July 26, 1982
GZA Engineering Corporation
75 Tarbile Hill Road
New Bedford, MA 02745

Items of Work	Est. Quantities Quantity	Unit of Measurement	Bid A Unit Price	Bid A Total Amount	Bid B Unit Price	Bid B Total Amount	Bid C Unit Price	Bid C Total Amount	Bid D Unit Price	Bid D Total Amount	Bid E Unit Price	Bid E Total Amount
Clearing and Grubbing	15	Acre	$ 2,800.00	$ 42,000.00	$ 3,500.00	$ 52,500.00	$ 3,000.00	$ 45,000.00	$ 2,500.00	$ 37,500.00	$ 3,600.00	$ 54,000.00
Removal of Existing Pipe (8-24")	50	l.f.	50.00	2,500.00	40.00	2,000.00	20.00	1,000.00	24.00	1,200.00	30.00	1,500.00
Fence Removal for Re-Use or Storage	2217	l.f	5.00	11,085.00	8.00	17,736.00	2.50	5,542.50	1.50	3,325.50	2.75	6,096.75
Common Excavation	145,000	c.y.	1.40	203,000.00	1.80	261,000.00	1.60	232,000.00	1.00	146,000.00	1.90	275,500.00
Unclassified Excavation	1	c.y.	200.00	200.00	50.00	50.00	100.00	100.00	6.00	6.00	30.00	30.00
Embankment-in-Place	145,000	c.y.	0.35	50,750.00	1.37	198,650.00	0.73	105,850.00	0.37	53,650.00	0.35	50,750.00
Fine Grading	1	Unit	50,000.00	50,000.00	6,000.00	6,000.00	12,000.00	12,000.00	83,650.00	83,650.00	75,000.00	75,000.00
Stockade Screen Fence	1376	l.f	9.50	13,072.00	9.45	13,003.20	12.50	17,200.00	13.62	18,741.12	12.30	16,924.80
Chainlink Fencing with Aluminum Coating	2100	l.f	11.25	23,625.00	12.29	25,809.00	17.25	36,225.00	13.44	28,224.00	12.50	26,250.00
Post Assemblies for 8' High Chainlink Fence	8	each	160.00	1,280.00	100.00	800.00	175.00	1,400.00	95.50	764.00	85.00	680.00

(Sheet 1 of 3)

Courtesy of New Hampshire Water Supply and Pollution Control Commission

9 3 1 2 9 0 4 1 2 4 5

TABLE B-1 (Continued)

Items of Work	Est. Quantities		Bid A		Bid B		Bid C		Bid D		Bid E	
	Quantity	Unit of Measurement	Unit Price	Total Amount	Unit Price	Total Amount	Unit Price	Total Amount	Unit Price	Total Amount	Unit Price	Total Amount
20' Wide Chainlink Fence	1	each	$ 1,000.00	$ 1,000.00	$ 700.00	$ 700.00	$ 750.00	$ 750.00	$ 320.00	$ 320.00	$ 300.00	$ 300.00
Removing Buildings and Fences	2217	l.f.	5.75	8,313.75	4.83	10,700.11	7.00	15,519.00	7.05	15,629.85	5.90	13,080.30
Loam 6" Deep	130,130	s.y	0.85	107,642.00	0.81	97,621.20	0.80	96,416.00	0.78	94,005.60	0.70	84,364.00
Limestone	40	ton	100.00	4,000.00	141.07	5,800.16	125.00	5,000.00	160.00	7,600.00	135.00	6,400.00
Fertilizer for Initial Application	8,000	lb	0.25	2,000.00	0.20	1,600.00	0.05	400.00	0.22	1,760.00	0.18	1,440.00
Fertilizer for Refertilization	40,000	lb	0.25	4,000.00	0.20	3,200.00	0.05	800.00	0.26	3,640.00	0.20	3,200.00
Park Seed Type 12 (pls wt)	1,160	lb	6.00	6,960.00	5.00	5,800.00	7.00	8,120.00	5.60	6,496.00	6.05	5,394.00
Slope Seed Type 33 (pls wt)	210	lb	6.00	1,260.00	5.25	1,102.50	7.00	1,470.00	5.70	1,197.00	4.75	997.50
Crownvetch Seed (pls wt)	30	lb	20.00	600.00	18.00	540.00	35.00	1,050.00	19.20	576.00	18.00	540.00
Mulch	5	acre	500.00	2,150.00	300.00	1,500.00	500.00	2,500.00	400.00	2,040.00	340.00	1,700.00

(Sheet 2 of 3)

TABLE B-1 (Concluded)

Item of Work	Est. Quantities Quantity	Est. Quantities Unit of Measurement	Bid A Unit Price	Bid A Total Amount	Bid B Unit Price	Bid B Total Amount	Bid C Unit Price	Bid C Total Amount	Bid D Unit Price	Bid D Total Amount	Bid E Unit Price	Bid E Total Amount
Netting for Erosion Control	7300	s.y.	$ 1.25	$ 9,325.00	$ 1.42	$ 10,366.00	$ 2.75	$ 20,075.00	$ 1.00	$ 7,300.00	$ 0.90	$ 6,570.00
Haybales	100	each	5.00	500.00	10.00	1,000.00	12.00	1,200.00	4.00	400.00	2.00	200.00
Seegrass for Temporary Erosion Control (pls wt)	100	lb	3.00	300.00	2.50	250.00	7.50	750.00	2.40	240.00	2.00	200.00
Gas Vents	11	each	350.00	3,850.00	520.00	5,720.00	500.00	5,500.00	600.00	6,600.00	500.00	5,500.00
SUB-TOTAL (All Items Above)	--	--	543,162.75		725,256.17		619,767.50		531,825.87		636,087.35	
Cutoff Wall Construction	204,000	s.f.	5.64	1,150,560.00	4.50	918,000.00	5.44	1,109,760.00	7.10	1,448,400.00	7.35	1,499,400.00
Off-site Borrow for Replacement of Contaminated Soil	7000	c.y.	6.00	42,000.00	3.50	24,500.00	5.00	35,000.00	3.42	23,940.00	13.70	95,900.00
Cash Allowance for Verification Testing by Engineer	--	lump sum	850,000.00		850,000.00		850,000.00		850,000.00		850,000.00	
Synthetic Membrane	98,466	s.y.	4.50	434,060.00	5.30	511,259.20	5.00	482,320.00	4.84	466,885.76	4.60	443,734.40
CONTRACTOR'S TOTAL BID PRICE	Total of Items 10,306.1, 306.3, 306.3, & 309		2,221,810.00		2,329,015.37		2,296,842.50		2,521,051.50		2,725,121.70	
MATHEMATICAL TOTAL			2,221,660.75		Same		2,296,847.50		2,521,051.63		2,725,121.75	

(Sheet 3 of 3)

B.2 Kin-Buc Landfill

The Kin-Buc sanitary landfill is located in Edison Township, Middlesex County, New Jersey, near the towns of Highland Park and Metuchen and just north of the Raritan River. The landfill is actually a mound composed of succeeding layers of wastes, all above original ground level. The geology at the site comprises a marine tidal marsh adjacent to the Raritan River, adjoining and overlying a permeable sand and gravel formation which dips southward beneath the river. Mean monthly temperatures in the area range between about 31°F (January) and 76°F (July); mean annual precipitation approximates 41 inches.

During the period 1973-1976, 70 million gallons of chemicals were dumped at the site (Fred C. Hart Associates, 1980). A set of environmental problems developed, and a lawsuit led to the withdrawal of the site's operating permit. Resolution of the lawsuit required as a first step the capping of the landfill, which was accomplished in 1980. It was expected that capping would mitigate the leachate-outflow problem.

The Kin-Buc landfill is approximately 20 acres in size and has roughly the shape of a mesa, with a flat top and sloping sides. The cover design consisted of regrading the top, placing a 12-in. layer of compacted clay overlain by a synthetic membrane, overlaying this with a 6-in. layer of sand, and finally placing a 12-in. layer of soil suitable for supporting vegetation. A carefully planned drainage system was incorporated. Around the edge of the top area a berm was constructed; just inboard of the berm is a drainage ditch with a perforated subdrain pipe buried beneath it. The ditches lead to downchutes located at three corners of the top area. The downchutes incorporated gabions in their construction and discharge to stilling basins, thus conveying water to the lower level without erosion.

The side slopes of the landfill are graded to a slope of about one in three. Capping of the slopes consisted of placing a layer of compacted clay, 6 to 12 in. thick, over the compacted wastes, and then covering the clay with 12 in. of soil suitable for supporting vegetation. Soil might slide off a membrane placed on slopes as steep as these. Near the base of the slopes a drainage ditch system with an outlying berm was designed to carry off the surface water flowing down the slopes.

Four gas vents were installed in the top of the landfill. These consisted of vertical PVC pipes the lower portion of which was perforated and set in a gravel-packed well in the wastes.

Figure B-8 is a plan view of the Kin-Buc landfill showing the layout of the drainage system. Various detailed aspects of the system are shown in Figures B-9-B-15. One of the downchutes may be seen in Figure B-16.

The drainage system is reported to have worked well to date (G. Tawadros, EPA Region II laboratory, personal communication). The only problem has been a certain amount of rill erosion on the slopes (Figure B-17). These rills are periodically filled and reseeded in an ongoing maintenance program.

FIGURE B-8

PLAN VIEW OF KIN-BUC LANDFILL, SHOWING DRAINAGE SYSTEM

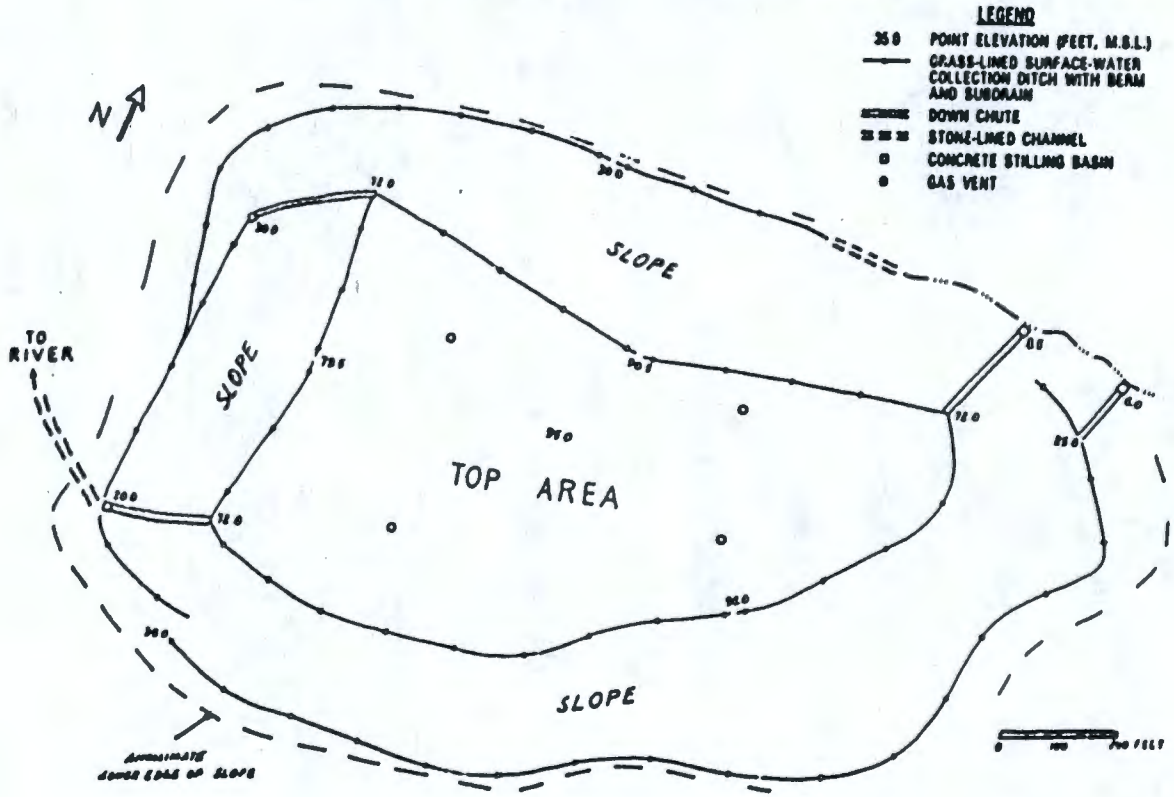
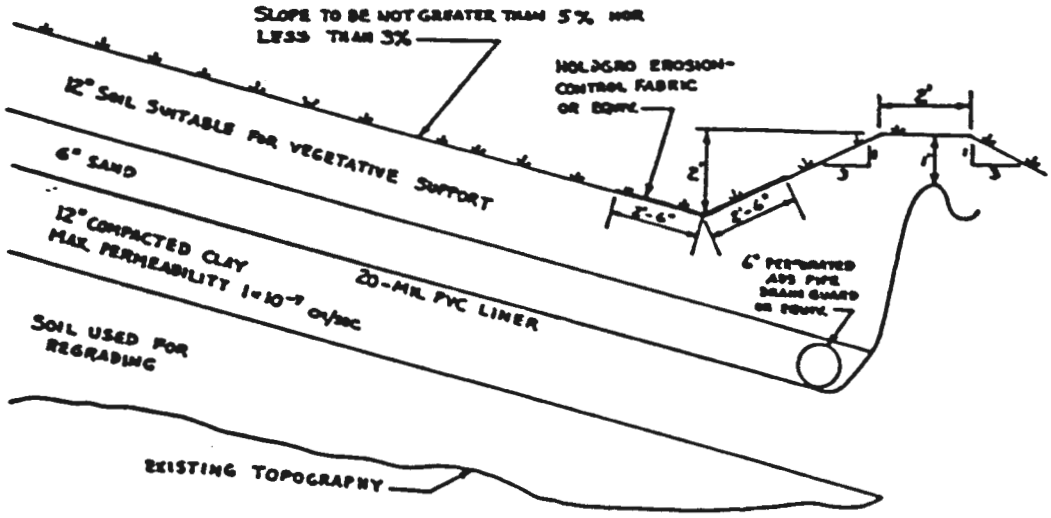


FIGURE B-9

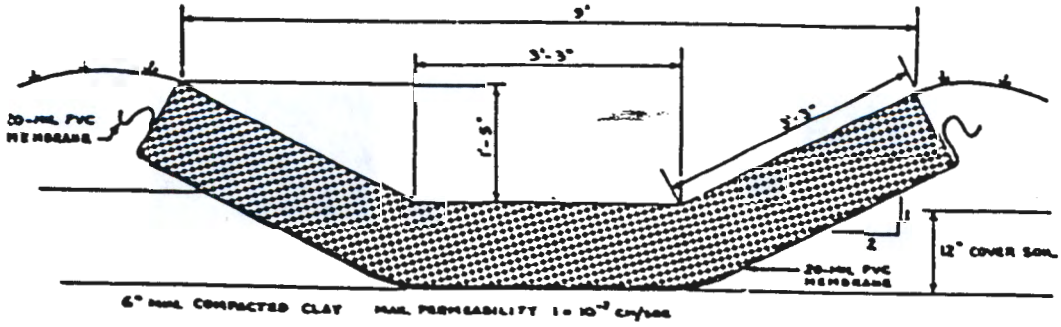
EDGE OF TOP AREA, DITCH AND BERM, KIN-BUC LANDFILL



TOP AREA / BERM AND COLLECTION DITCH DETAIL
N.T.S.

FIGURE B-10

DOWNCHUTE SECTION, KIN-BUC LANDFILL



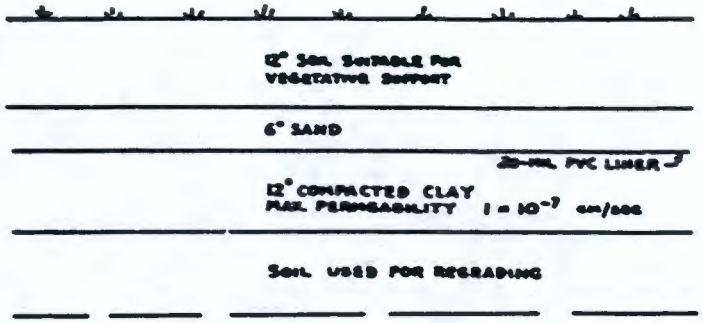
DOWNCHUTE SECTION

NOTES

1. CHANNEL SECTION TO BE CONSTRUCTED OF GABIONS SERIES 320 MANUFACTURED BY MACCAFERRI GABIONS, INC. OR EQUIV.
2. SIZE OF STONE FILL TO BE 4" MIN.
3. SIZE OF GABIONS WITH CHANNEL SECTION TO BE 6'-6" × 3'-3" × 1'-0"

FIGURE B-11

COVER SOIL SECTION, TOP AREA, KIN-BUC LANDFILL

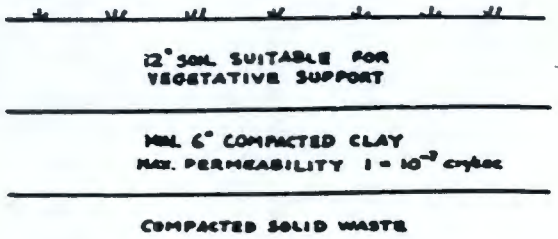


FINAL COVER FOR TOP SURFACE

N.T.S.

FIGURE B-12

COVER SOIL SECTION, SIDE SLOPE AREA, KIN-BUC LANDFILL



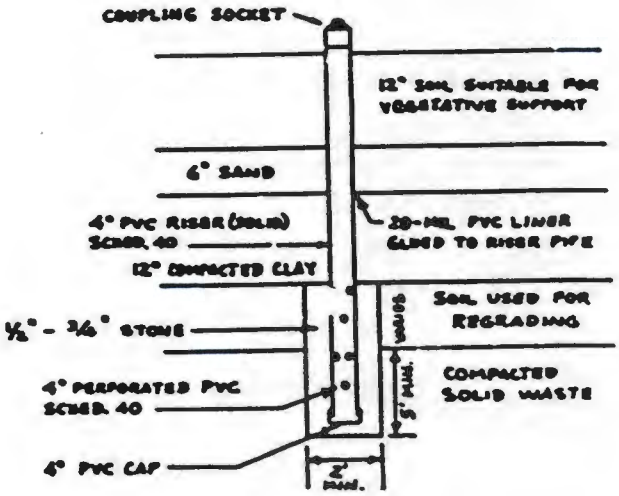
FINAL COVER FOR SIDE SLOPES

N.T.S.

9312904125 0

FIGURE B-13

GAS VENT DETAIL, KIN-BUC LANDFILL



DETAIL OF GAS VENT

N.T.S.

FIGURE B-14

GRASSED CHANNEL SECTION, KIN-BUC LANDFILL

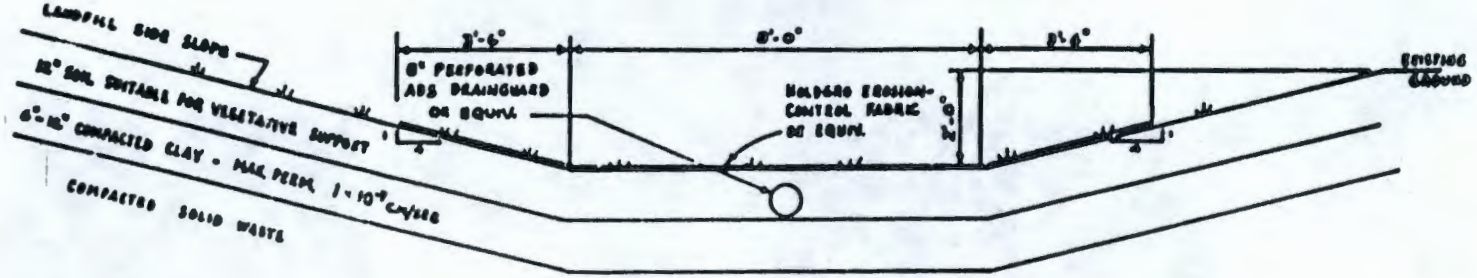


FIGURE B-15

SIDE-HILL DITCH AND BERM, KIN-BUC LANDFILL

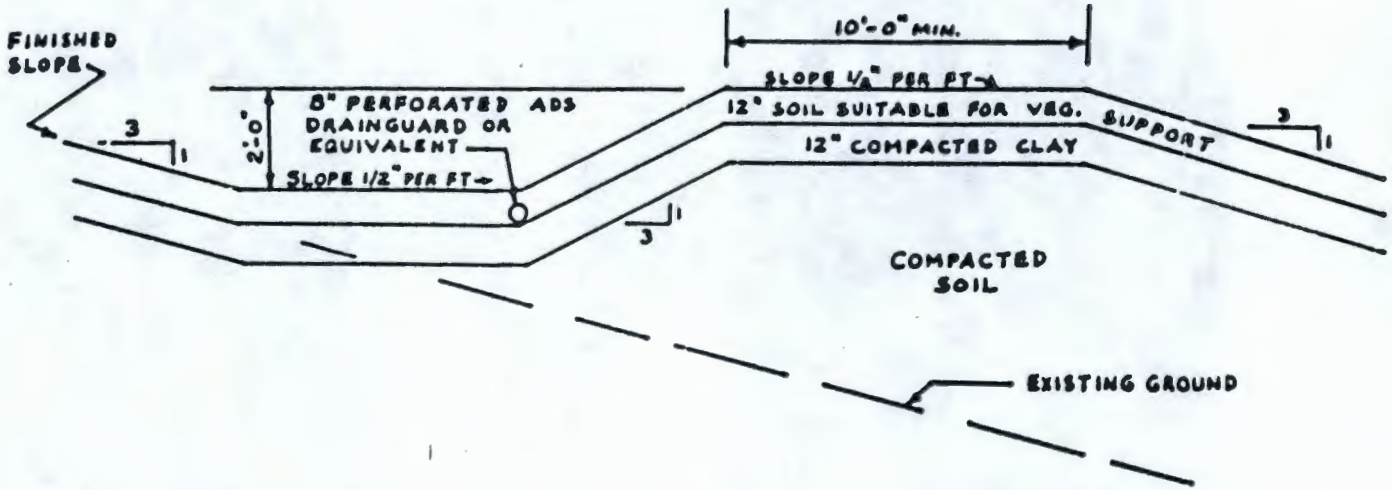


FIGURE B-16

DOWNCHUTE AT ONE CORNER OF KIN-BUC LANDFILL

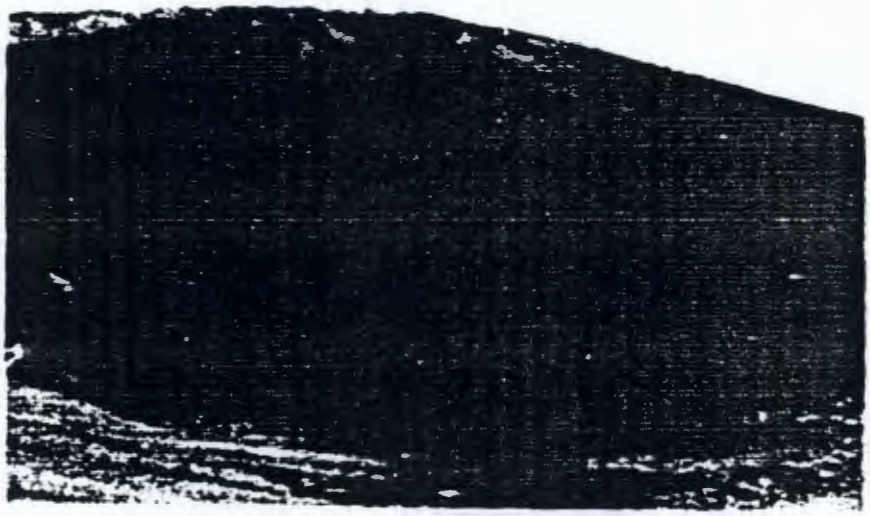
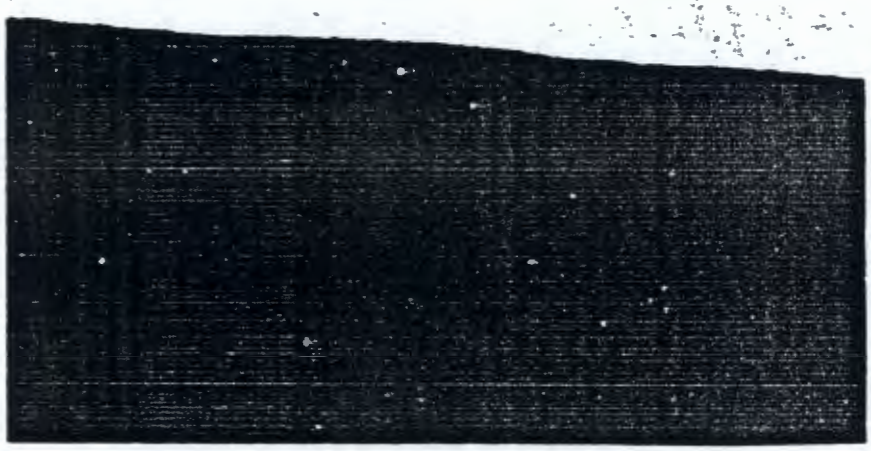


FIGURE B-17

RILL EROSION IN SIDE SLOPES, KIN-BUC LANDFILL



9 3 1 2 9 0 4 1 2 5 3

APPENDIX C

COSTS

It has not been feasible to prepare a complete discussion of costs for cover-system design and construction. A good example of such a discussion is Chapter 7 of Spooner et al. (1984), which treats in detail the major cost elements for slurry-trench design and construction. Since several problems and activities are common to the construction of slurry trenches and covers, it is recommended that the cover designer consult this reference.

In an effort to develop usable cost information for Superfund remedial-response actions, Rishel, Boston, and Schmidt (1981) performed a detailed conceptual study of the costs of remedial measures at landfills and surface impoundments. They identified 35 "unit operations" (UO), 21 for landfills and 14 for impoundments. Examples of UO would be "Ponding" and "Sheet Pile Cut-Off Wall." Each UO was analyzed into its components, and these were then costed for the specific case of Newark, NJ, and also for estimated lower-average and upper-average costs for the U. S. Both Capital and Operation-and-Maintenance (O&M) costs were considered. A wealth of cost information was developed (in terms of mid-1980 dollars).

The tables listed below are from Rishel, Boston, and Schmidt (1981). The cover designer should be able to recognize those items that pertain to cover systems.

Table No.	Title
C-1	Capital and O&M Components Which Contribute to Unit Operations
C-2	Average U. S. Low and High Costs of Unit Operations for Medium-Sized Sites (Metric Units)*
C-3	Landfill Capital Cost Components - Metric Units
C-4	Landfill O&M Cost Components - Metric Units
C-5	Surface Impoundment Capital Cost Components - Metric Units
C-6	Surface Impoundment O&M Cost Components - Metric Units

* Rishel, Boston, and Schmidt present equivalent tables in English units, but list cost-data sources only in their Metric tables. For this reason the Metric tables have been reproduced here.

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The cover designer will find this report instructive, and it is highly recommended. The authors offer a distinct caveat regarding use of their cost figures, however, and it is considered appropriate to reproduce it here (Rishel, Boston, and Schmidt, 1981, p 3):

> "QUALIFICATIONS AND LIMITATIONS OF RESULTS
>
> "The overall objective of this study was to estimate the cleanup costs of hazardous-waste sites using a conceptual-design approach. This approach was necessitated by the fact that "Superfund" remedial-response activities are still in their infancy, and that real-world feedback on the cost of these hazardous-waste cleanup activities is largely unavailable.
>
> "In using these cost estimates, the reader should exercise considerable caution. Cost estimates are only as complete as the unit operations they describe, or as realistic as the various assumptions and site profiles upon which they are based.
>
> "A subsequent volume to this report will use real-life experiences in actual hazardous-waste-site remedial actions to refine this volume's costing methodology."

The cover-system designer considering the importation of bulk materials will find an informative discussion of the economics of bulk shipments by various modes of transportation in Collins and Miller (1976, pp 241-267).

The actual bid figures for remedial construction at the Sylvester hazardous waste site, Nashua, NH, are presented in "Case Histories" (Appendix B).

A table of year-to-year cost indices is presented in Appendix C of JRB Associates, Inc. (1982).

C-3

TABLE C-1

CAPITAL AND O&M COMPONENTS WHICH CONTRIBUTE TO UNIT OPERATIONS

	Unit Operations	Cumulative cost of unit operations
LANDFILL	1. Contour grading	1,20,11
	2. Surface sealing	[illegible]
	3. Revegetation	[illegible]
	4. Bentonite wall	[illegible]
	5. Grout curtain	[illegible]
	6. Sheet piling wall	[illegible]
	7. Grout bottom sealing	[illegible]
	8. Drains	[illegible]
	9. Well point system	[illegible]
	10. Deep well system	[illegible]
	11. Injection	[illegible]
	12. Subgrade irrigation	1,1
	13. Chemical fixation	1,1
	14. Chemical injection	
	15. Excavation/burial	
	16. Ponding	1,1
	17. Trench construction	
	18. Perimeter trench vents	
	19. Ground water treatment	1,18
	20. Gas control-passive	1
	21. Gas control-active	
IMPOUNDMENTS	22. Pond closure/grading	11,14
	23. Surface sealing	11,11
	24. Revegetation	11,11
	25. Slurry trench	11,14,30,11
	26. Grout curtain	11,14,30,31
	27. Sheet piling wall	11,14,30,31
	28. Grout bottom seal	[illegible]
	29. Toe and Underdrains	11,14,30,11
	30. Well point system	11,11,11
	31. Deep well system	11,21,11
	32. Well injection	11,31,11
	33. Leachate treatment	
	34. Berm reconstruction	
	35. Excavation/disposal	

CAPITAL COSTS

O & M COSTS

TABLE C-2

AVERAGE U. S. LOW AND HIGH COSTS OF UNIT OPERATIONS FOR MEDIUM-SIZED SITES - METRIC UNITS

Unit Operations	Typical Metric Unit	Average U.S. Low Cost Per Unit			Average U.S. High Cost Per Unit		
		Initial Capital $	First Year O&M $	Life Cycle Cost $	Initial Capital $	First Year O&M $	Life Cycle Cost $
1. Contour grading and surface water diversion	Site area, ha	15,300	114	16,300	17,900	240	19,900
2. Bituminous concrete surface sealing	Site area, ha	67,300	0	67,300	92,700	0	92,700
3. Revegetation	Site area, ha	3,450	105	14,300	16,500	185	18,100
4. Bentonite slurry trench cutoff wall	Wall face area, m^2	54.5	0.002	61.7	96.1	0.077	103
5. Grout curtain	Wall face area, m^2	600	0.00	937	1,200	0.00	1800
6. Sheet piling cutoff wall	Wall face area, m^2	73	0	73	188	0	188
7. Grout bottom sealing	Site area, ha	5,787,000	1,600	5,796,000	10,209,000	1,750	10,226,000
8. Drains	Pipe length, m	72.7	33.7	357	106	36.8	416
9. Well point system	Interceptor face area, m^2	62.5	5.23	107	105	6.64	153
10. Deep well system	Interceptor face area, m^2	11.6	2.1	28.6	18.3	2.22	37.2
11. Injection	Interceptor face area, m^2	77	199	1,760	90	201	1,785
12. Leachate recirculation by subgrade irrigation	Site area, ha	9,270	1,700	19,700	8,340	1,850	24,000
13. Chemical fixation	Site area, ha	69,100	1,600	82,500	130,000	1,750	145,000
14. Chemical injection	Landfill volume, m^3	1.67	.0577	2.16	3.28	.0631	3.81
15. Excavation and reburial	Landfill volume, m^3	116	0.015	116	120	0.016	120

(Continued)

(continued)

TABLE C-2 (Concluded)

Unit Operations	Typical Unit/Unit Units	Average U.S. Low Cost Per Unit			Average U.S. High Cost Per Unit		
		Initial Capital $	First Year O&M $	Life Cycle Cost $	Initial Capital $	First Year O&M $	Life Cycle Cost $
16. Ponding	Site area, ha	647	0	647	1,030	0	1,030
17. Trench construction	Trench length, m	12.7	0.344	15.11	16.34	0.710	20.32
18. Perimeter gravel trench weeds	Trench length, m	99.7	0.110	100	144	0.257	144
19. Treatment of contaminated ground water	Contaminated water, l/d	1.52	0.110	2.52	2.57	0.214	4.30
20. Gas migration control - passive	Site perimeter, m	101	0.013	100	241	1.71	250
21. Gas migration control - active	Site perimeter, m	113	6.36	167	173	12.6	270
22. Pond closure and contour grading of surface	Site area, ha	26,000	1,070	35,000	35,100	2,100	63,500
23. Bituminous concrete surface sealing of closed impoundment	Site area, ha	48,500	0	48,500	70,700	0	70,700
24. Revegetation	Site area, ha	2,540	171	3,970	3,870	192	5,650
25. Slurry trench cutoff wall	Wall face area, m^2	60.1	0	60.1	105	0	105
26. Grout curtain	Wall face area, m^2	370	1.04	343	631	2.12	649
27. Sheet piling cutoff wall	Wall face area, m^2	76.0	2.11	94.0	115	2.31	135
28. Grout bottom seal	Site area, ha	860,000	18,500	1,024,000	1,021,000	20,300	1,197,000
29. Toe and underdrains	Pipe length, m	516	166	1,550	600	160	1,900
30. Well point system	Intercept face area, m^2	62.5	32.5	321	117	33.2	300
31. Deep well system	Intercept face area, m^2	33.2	9.90	116.4	60.3	10.6	1[illegible]
32. Well injection system	Intercept face area, m^2	31.3	9.22	104	66.0	10.1	161
33. Leachate treatment	Contaminated water, L/d	1.16	0.301	4.69	1.06	0.230	0.14
34. Berm reconstruction	Replaced berm, m^3	2.06	0.222	4.00	3.00	0.366	5.05
35. Excavation and disposal at secure landfill	Impoundment volume, m^3	260	0	260	260	0	260

TABLE C-3

LANDFILL CAPITAL COST COMPONENTS - METRIC UNITS

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Branch
Apply stabilized waste	Installation	Hauling and spreading, 10 miles (16 km), round trip	$/m^3	Moore 1980	8.76	3.52	11.6	10.0
Area preparation	Labor	Bake and cleanup, average	$/ha	Dodge 1980	741	660	963	830
Area preparation	Equipment	Bake and cleanup, average	$/ha	Dodge 1980	222	222	222	222
Backfill	Labor	Dozer and sheepsfoot roller	$/m^3	Moore 1980	0.61	0.32	0.64	0.58
Backfill	Equipment	Dozer and sheepsfoot roller	$/m^3	Moore 1980	1.44	1.44	1.44	1.44
Bentonite, delivered	Materials/shipping	Shipment of bentonite by rail	$/tonne	Burlington Northern 1980		66.4	177	166
Berm construction	Materials/installation	Use scraper	$/m^3	Dodge 1980	0.50	0.35	0.60	0.52
Blower	Materials/installation	Blower, air	$/each	Britton 1980	1,150	800	1,360	1,200
Butterfly valves, 6"	Materials/installation	PVC valve	$/each	Godfrey 1980	192	135	230	200
Butterfly valves, 8"	Materials/installation	PVC valve	$/each	Godfrey 1980	304	213	360	317
Cement pipe, 4" perforated	Labor	Asbestos, Class 4000 underdrain	$/m	Moore 1980	3.00	1.90	3.18	2.82
Cement pipe, 4" perforated	Materials	Asbestos, Class 4000 underdrain	$/m	Moore 1980	5.00	3.91	5.38	4.77
Cement pipe, 6" perforated	Labor	Asbestos, Class 4000 underdrain	$/m	Moore 1980	5.10	1.95	4.06	3.53
Cement pipe, 6" perforated	Materials	Asbestos, Class 4000 underdrain	$/m	Moore 1980	8.00	6.16	8.48	7.52
Cement pipe, 6"	Labor	Cement pipe, non-perforated	$/m	Moore 1980	3.34	2.23	4.63	4.06
Cement pipe, 6"	Materials	Cement pipe, non-perforated	$/m	Moore 1980	6.23	4.60	6.60	5.85
Chemicals	Materials	Treatment chemical, sodium hydrochlorite (NaClO)	$/l	Puron 1980	0.16	0.12	0.17	0.15
Deep wells, 8"	Material./labor	Drilled and cased	$/m	Moore 1980	20.9	14.6	25.1	21.8
Dewatering system	Materials/labor	For cost breakdown, see "Discharge pipe," "submersible pump," "Deep wells"						
Discharge pipe, 4"	Labor	PVC plastic, Schedule 40	$/m	Moore 1980	22.0	13.9	28.8	25.1
Discharge pipe, 4"	Materials	PVC plastic, Schedule 40	$/m	Moore 1980	9.15	7.05	9.70	6.60

(Sheet 1 of 5)

(continued)

TABLE C-3 (Continued)

Component	Subcomponent	Definition	Metric Unit	Source	Source Cost	Low	High	Recent
Discharge pipe, 8"	Labor	PVC plastic, Schedule 40	$/m	Means 1980	34.1	21.5	44.7	28.0
Discharge pipe, 8"	Materials	PVC plastic, Schedule 40	$/m	Means 1980	27.4	21.1	79.0	25.0
Diversion ditch, construction	Installation	Construction and maintenance/repair	$/m^3	Means 1980	2.78	1.75	3.63	3.13
Drilled holes, 3.5"	Materials/installation	Drilled and cased with pipe	$/m	Means 1980	18.3	11.6	24.1	20.9
Drilled holes, 6"	Materials/installation	Drilled and cased with pipe	$/m	Means 1980	22.3	15.6	26.4	23.2
Drill rig	Rental (Equip./labor)	Crew one light duty rig, and grouting	$/day	Means 1980	400	200	670	420
Excavation, drainage trench	Labor	One backhoe loader	$/m^3	Means 1980	2.65	1.70	3.50	3.00
Excavation, drainage trench	Materials	One backhoe loader	$/m^3	Means 1980	1.60	1.30	1.70	1.50
Excavation/grading, soil	Labor	Excavation/grading, soil, common borrow, 1000 ft (305 m) haul	$/m^3	Dodge 1980	0.22	0.14	0.29	0.25
Excavation/grading, soil	Equipment	Excavation/grading, soil, common borrow, 1000 ft (305 m) haul	$/m^3	Dodge 1980	0.76	0.76	0.76	0.76
Excavation, grading, and recontouring of site	Labor	300 ft (90 m) haul, dozer and truck	$/m^3	Means 1980	0.37	0.23	0.48	0.42
Excavation, grading and recontouring of site	Equipment	300 ft (90 m) haul, dozer and truck	$/m^3	Means 1980	1.35	1.35	1.35	1.35
Exploratory boring	Materials/installation	Test strata in or below landfill, and to apply chemical injection 4 in. (0.03 m) diameter holes	$/m	Means 1980	19.7	13.8	23.2	20.5
Flow meters, 6"	Materials/installation	Measures rate of flow of landfill gas to blower	$/each	Godfrey 1980	800	550	1,150	1,002
Flow meters, 8"	Materials/installation	Measures rate of flow of landfill gas to blower	$/each	Godfrey 1980	1,040	650	1,360	1,100
Geotechnical investigation	Labor/materials	Includes exploratory holes, surveying mobilization, drilling addition, pump test, and report	$/site	SCS 1980	5,500	3,850	6,520	5,720
Gravel	Labor	One dozer operator, one truck driver	$/m^3	Means 1980	2.48	1.56	3.25	2.50
Gravel	Materials	3/4" screened gravel	$/m^3	Means 1980	7.20	5.34	7.63	7.50
Grout curtain	Labor	Two grid - phenolic resin (also for grout bottom seal)	$/m^3	Means 1980	267	165	343	290
Grout curtain	Materials	Two grid - phenolic resin (also for grout bottom seal)	$/m^3	Means 1980	56.2	43.3	59.6	52.8

(Sheet 2 of 3)

(continued)

TABLE C-3 (Continued)

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Average
Header pipe, 8"	Materials	PVC Schedule 40	$/m	Means 1980	27.6	21.1	29.0	25.8
Header pipe, 8"	Installation	PVC Schedule 40	$/m	Means 1980	36.1	21.5	44.7	30.9
Hydroseeding	Labor	Includes seed and soil supplements	$/ha	Dodge 1980	171	100	224	195
Hydroseeding	Materials	Includes seed and soil supplements	$/ha	Dodge 1980	877	675	929	826
Hydroseeding	Equipment	Includes seed and soil supplements	$/ha	Dodge 1980	126	126	126	126
Liner	Labor/materials	30 mil bracketed with heavyweight geotextile fabric, Hypalon	$/m^2	Dupont 1980	6.22	6.35	7.37	6.67
Materials testing	Materials/installation	For testing, see "Exploratory Boring"						
Moisture traps	Materials/installation	Remove water from gas control system	$/each	NAA Cons. 1980	480	335	570	500
Monitoring equipment	Equipment	Gas detection instrumentation to monitor gas control systems (NAA Model 53 Gascope)	$/each	SCS 1980	500	500	500	500
Monitoring wells, gas	Materials	0.5" (1.3 cm), 12 ft (3.6 m) deep, for landfill gas monitoring	$/m	Means 1980	1.36	1.05	1.42	1.26
Monitoring wells, gas	Installation	0.5" (1.3 cm), 12 ft (3.6 m) deep, for landfill gas monitoring	$/m	Means 1980	8.82	5.55	11.5	10.0
Mulching	Labor	Hay mulching	$/ha	Dodge 1980	85.2	53.7	111	97.1
Mulching	Materials	Hay mulching	$/ha	Dodge 1980	210	167	223	197
Mulching	Equipment	Hay mulching	$/ha	Dodge 1980	57.3	57.3	57.3	57.3
Pipe, PVC (elbows), 6"	Materials	90° fitting	$/each	Means 1980	27.0	20.0	28.6	25.6
Pipe, PVC (elbows), 6"	Installation	90° fitting	$/each	Means 1980	20.0	17.6	36.7	31.9
Pipe, PVC (elbows), 8"	Materials	90° fitting	$/each	Means 1980	52.0	40.0	55.1	48.9
Pipe, PVC (elbows), 8"	Installation	90° fitting	$/each	Means 1980	39.3	26.6	51.1	46.5
Pipe, PVC (Tees), 6"	Materials	T-fittings for gas wells	$/each	Means 1980	37.0	28.5	35.2	34.8
Pipe, PVC (Tees), 6"	Installation	T-fittings for gas wells	$/each	Means 1980	46.0	29.0	60.3	52.4
Pipe, PVC (Tees), 8"	Materials	T-fittings for gas wells	$/each	Means 1980	75.0	57.0	79.5	70.5
Pipe, PVC (Tees), 8"	Installation	T-fittings for gas wells	$/each	Means 1980	59.0	37.2	77.3	67.3
Pipe, PVC, laterals, 8"	Materials	For gas extraction wells, Schedule 40 (includes $4.92/m for perforations)	$/m	Means 1980	29.70	22.6	30.9	27.6

(Sheet 3 of 5)

(continued)

TABLE C-3 (Continued)

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Average
Pipe, PVC, laterals, 8"	Installation	For gas extraction wells, Schedule 40	$/m	Means 1990	9.65	6.00	12.6	11.0
Pipe, PVC, laterals, 12"	Materials	For gas extraction wells, Schedule 40 (includes $4.02/m for perforations)	$/m	Means 1990	41.0	31.6	43.7	38.6
Pipe, PVC, laterals, 12"	Installation	For gas extraction wells, Schedule 40	$/m	Means 1990	15.4	11.9	16.4	14.5
Pipe, PVC, risers, 6"	Materials	For gas extraction wells, Schedule 40	$/m	Means 1990	9.15	7.01	9.70	8.60
Pipe, PVC, risers, 6"	Installation	For gas extraction wells, Schedule 40	$/m	Means 1990	22.0	13.9	28.8	25.1
Pipe, PVC, risers 6"	Materials	For gas extraction wells, Schedule 40	$/m	Means 1990	16.6	12.7	17.4	15.6
Pipe, PVC, risers 6"	Installation	For gas extraction wells, Schedule 40	$/m	Means 1990	25.7	16.7	33.7	30.8
Pump, centrifugal	Equipment/installation	1/6 HP pump	$/each	Means 1990	1,600	1,600	1,600	1,600
Pump, submersible	Labor	1 HP - 4", submersible	$/each	Means 1990	344	220	450	390
Pump, submersible	Materials	1 HP - 4" submersible	$/each	Means 1990	425	130	450	400
Recharge trench	Materials/installation	Excavation of trench	$/m^3	Means 1990	1.60	1.12	1.90	1.66
Sand	Materials/installation	For well point caving backfill	$/bag	Means 1990	5.00	4.06	6.07	6.03
Sheet piling	Materials	Steel sheet, PMA-22 (22 lbs/ft^2)	$/tonne	Means 1990	587	390	537	477
Sheet piling	Installation	Install steel sheet, PMA-22 (22 lbs/ft^2)	$/tonne	Means 1990	100	63	131	116
Slurry trench excavation	Materials/installation	Includes installation of bentonite slurry	$/m^3	Means 1990	46.0	32.2	56.5	47.8
Spread excavated material	Labor	One equipment operator, five laborers	$/m^3	Means 1990	0.21	0.13	0.25	0.22
Spread excavated material	Equipment	Spread by dozer, no compaction	$/m^3	Means 1990	0.51	0.51	0.51	0.51
Surface seal, bituminous concrete	Installation	1" (0.08 m) thick cap	$/m^2	Means 1990	1.05	0.66	1.37	1.20
Surface seal, bituminous concrete	Material	1" (0.08 m) thick cap	$/m^2	Means 1990	3.00	2.31	3.18	2.82
Surface seal, clay cap	Materials/installation	6" (15-cm) clay cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	4.82	3.50	6.41	5.49
Surface seal, clay cap	Materials/installation	18" (46-cm) clay cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.18	4.51	8.22	7.05
Surface seal, fly ash cap	Materials/installation	12" (30-cm) fly ash, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	4.65	3.40	6.17	5.30

(Sheet 4 of 5)

(continued)

TABLE C-3 (Concluded)

Component	Subcomponent	Definition	Metric Unit	Source	Source Cost	Low	High	Remark
Surface seal, fly ash cap	Materials/installation	24" (60-cm) fly ash cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.27	4.49	8.36	7.15
Surface seal, lime-stabilized cap	Materials/installation	5" (13-cm) lime-stabilized cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.05	3.24	8.04	6.90
Surface seal, PVC membrane cap	Materials/installation	30-mil PVC membrane cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	10.8	9.7	14.4	12.3
Surface seal, soil-cement cap	Materials/installation	5" (13-cm) soil-cement cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.05	3.34	8.04	6.90
Surveying	Labor	Labor cost/day, establish surface topographic profile	$/day	SCS 1980	220	150	240	220
Tipping fees	Unit costs	Dumping and grading costs at new site	$/tonne	SCS 1979	110	110	110	110
Transportation	Labor/equipment	30-ton dump truck/driver, based on one-way hauling distance, return trip included	$/tonne-km	SCS 1981	0.096	0.060	0.128	0.109
Transportation	Labor/equipment	15-ton dump truck/driver, based on one-way hauling distance, return trip included	$/tonne-km	SCS 1981	0.110	0.069	0.143	0.125
Treatment system	Unit costs	Typical costs - interpolated @ 0.12 MGD (440,000 l/d)	$/each	Dodge 1980	580K	400K	687K	602K
Trench excavation	Labor	One equipment operator/one laborer	$/m^3	Neane 1980	0.22	0.17	0.35	0.31
Trench excavation	Equipment	Tractor or hydraulic backhoe to excavate trench, sloped 1/2 to 1	$/m^3	Neane 1980	1.16	1.16	1.16	1.16
Well points, 2.5" (6.4 cm) dia	Materials/installation	PVC, 25 feet (7.6 m)	$/m	Davis 1980	59.3	41.5	70.3	61.7
Wellpoint fittings	Materials/installation	Fittings and accessories	$/well	Davis 1980	12.0	8.40	14.2	12.5

(Sheet 5 of 5)

TABLE C-4

LANDFILL O&M COST COMPONENTS - METRIC UNITS

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Rough
Chemicals	Materials	Wastewater/leachate treatment plant chemicals	$/l/day (influent)	SCS 1980	0.025	0.025	0.025	0.025
Electricity	Power costs	For water treatment plant, extraction, injection, and gas control well/pumps	$/kwh	SCS 1980	0.05	0.05	0.05	0.05
Grubbing	Labor/equipment	Assume annual grubbing (clearing) of brush	$/m^2	Dodge 1980	0.19	0.12	0.25	0.22
Maintenance/repair, diversion ditch	Installation	Assume diversion ditch needs rebuilding 2 times a year after major storms	$/m^3	Means 1980	2.75	1.73	3.60	3.14
Monitoring	Labor	For gas monitoring at active and passive gas control installations	$/hr	SCS 1980	12.5	7.88	16.6	14.3
Monitoring (analysis)	Laboratory costs	For ground water/leachate monitoring from monitoring wells	$/sample	SCS 1980	330	330	330	330
Monitoring (sampling)	Labor	For ground water/leachate monitoring from monitoring wells	$/hr	SCS 1980	12.5	7.88	16.6	14.3
Grass mowing	Labor/materials	Use 50" power ride mower, one operator	$/ha	Dodge 1980	93.9	66.7	111	98.9
Operating cost	Labor	For water treatment plant operating personnel	$/hr	SCS 1980	10	6.30	13.10	11.30
Operating cost	Labor	For gas collection system operating personnel	$/hr	SCS 1980	15	9.45	19.95	17.10
Refertilization	Labor/materials	Assume refertilization once per year	$/ha	Dodge 1980	341	247	396	346
Water	Materials	Industrial process water	$/kl	SCS 1980	0.92	0.92	0.92	0.92

TABLE C-5

SURFACE IMPOUNDMENT CAPITAL COST COMPONENTS - METRIC UNITS

Component	Subcomponent	Definition	Metric Unit	Source	Source Cost	Low	High	Remark
Area preparation	Labor	For area preparation, rake and clean up, average	$/m^2	Dodge 1980	0.074	0.047	0.096	0.084
Area preparation	Equipment	For area preparation, rake and clean up, average	$/m^2	Dodge 1980	0.022	0.022	0.022	0.022
Bentonite, delivered	Materials/shipping	Shipment of bentonite by rail near job site, includes materials and delivery	$/tons	Burlington Northern 1980		66.4	177	166
Cement pipe, 6"	Materials	Class 4000, perforated, asbestos	$/m	Means 1980	8.00	6.16	8.48	7.52
Cement pipe, 6"	Installation	Class 4000, perforated, asbestos	$/m	Means 1980	3.10	1.95	4.06	3.53
Discharge trench	Labor	Including backfill 3 ft (1 m) deep	$/m^3	Means 1980	1.97	1.24	2.58	2.23
Discharge trench	Equipment	Including backfill 3 ft (1 m) deep	$/m^3	Means 1980	1.57	1.57	1.57	1.57
Diversion ditch, Construction	Installation	Construction and maintenance/repair	$/m^3	Means 1980	2.78	1.75	3.63	3.13
Drilled holes, 6"	Materials/installation	Drilled and cased with pipe	$/m	Means 1980	22.3	15.6	26.4	23.2
Drill rig	Rental (Equipment/labor)	Crew and light-duty rig	$/day	Means 1980	400	280	470	420
Excavation	Labor	One equipment operator	$/m^3	Means 1980	0.16	0.10	0.21	0.18
Excavation	Equipment	Front end loader	$/m^3	Means 1980	0.65	0.65	0.65	0.65
Excavating/grading, soil	Labor	Common borrow (earth), 1000 ft (305 m) haul	$/m^3	Dodge 1980	0.27	0.14	0.29	0.23
Excavating/grading, soil	Equipment	Common borrow (earth), 1000 ft (305 m) haul	$/m^3	Dodge 1980	0.76	0.76	0.76	0.76
Geotechnical investigation	Unit costs	Includes surveying, test borings, equipment, mobilization, monitoring wells, pump tests, report	$/each	SCS 1980	14,500	9,500	19,500	16,900
Geotechnical investigation	Unit costs	Slurry wall testing	$/each	SCS 1980	2,000	1,260	2,620	2,200
Gravel	Labor/installation	3/4" screened gravel, one dozer operator, one truck driver	$/m^3	Means 1980	2.48	1.56	3.25	2.50
Gravel	Materials	3/4" screened gravel, one dozer operator, one truck driver	$/m^3	Means 1980	7.20	5.54	7.63	7.50
Grout curtain	Labor	Chemical grout, phenolic resin, 2-grid	$/m^3	Means 1980	267	165	343	298

(Sheet 1 of 3)

(continued)

TABLE C-5 (Continued)

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Growth
Grout curtain	Materials	Chemical grout, phenolic resin, 2-grid	$/m^3$	Means 1980	56.2	43.3	59.6	52.8
Header and discharge pipe, 8"	Materials	PVC class 150 pipe, laid in trench	$/m	Means 1980	24.2	18.6	25.6	22.7
Header and discharge pipe, 8"	Installation	PVC class 150 pipe, laid in trench	$/m	Means 1980	9.61	6.05	12.6	10.9
Hydroseeding	Labor	Seed and soil supplements/amendments	$/m^2$	Dodge 1980	0.0171	0.0100	0.0224	0.0195
Hydroseeding	Materials	Seed and soil supplements/amendments	$/m^2$	Dodge 1980	0.0077	0.0075	0.0020	0.0024
Hydroseeding	Equipment	Hydroseeding	$/m^2$	Dodge 1980	0.0124	0.0124	0.0124	0.0124
Mulching	Labor	Mulching hay	$/m^2$	Dodge 1980	0.0085	0.0054	0.0112	0.0097
Mulching	Materials	Mulching hay	$/m^2$	Dodge 1980	0.0210	0.0162	0.0223	0.0197
Mulching	Equipment	Mulching hay	$/m^2$	Dodge 1980	0.0057	0.0057	0.0057	0.0057
Pump, centrifugal	Equipment/installation	3/4 HP pump	$/each	Means 1980	1,600	1,600	1,600	1,600
Pump, submersible	Labor/installation	1 HP, 4", including wiring	$/each	Means 1980	344	220	450	390
Pump, submersible	Materials	1 HP, 4", including wiring	$/each	Means 1980	424	330	450	400
Sheet piling	Labor/equipment/ installation	PSA-22 steel sheet piling (22 lbs/ft^2)	$/tonne	Means 1980	100	63	131	114
Sheet piling	Materials	PSA-22 steel sheet piling (22 lbs/ft^2)	$/tonne	Means 1980	507	350	537	476
Slurry wall, installation	Installation	Install slurry compound in excavated trench	$/m^3	Means 1980	45.9	32.2	54.5	47.8
Slurry wall testing	Unit cost	See "Geotechnical Investigation, Slurry wall testing"						
Soil compacting	Labor	With sheepsfoot roller	$/m^3	Means 1980	0.63	0.40	0.83	0.71
Soil compacting	Equipment	With sheepsfoot roller	$/m^3	Means 1980	0.06	0.06	0.06	0.06
Sump	Labor/equipment	16 ft (5 m) deep x 8" (20 cm) thick concrete, cost in place	$/each	Means 1980	820	514	1,074	926
Sump	Materials	16 ft (5 m) deep x 8" (20 cm) thick concrete, cost in place	$/each	Means 1980	750	577	795	705

(Sheet 2 of 3)

(continued)

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TABLE C-5 (Concluded)

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Bench
Surface seal, bituminous concrete	Labor/equipment	3" (0.08 m) thick cap	$/m^2	Moore 1980	1.05	0.72	1.34	1.09
Surface seal, bituminous concrete	Materials	3" (0.08 m) thick cap	$/m^2	Moore 1980	3.00	2.31	3.10	2.82
Surface seal, clay cap	Materials/installation	6" (15-cm) clay cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	4.82	3.50	6.41	5.49
Surface seal, clay cap	Materials/installation	18" (46-cm) clay cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.18	4.51	8.22	7.05
Surface seal, fly ash cap	Materials/installation	12" (30-cm) fly ash cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	4.60	3.40	6.18	5.24
Surface seal, fly ash cap	Materials/installation	24" (60-cm) fly ash cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.28	4.49	8.36	7.15
Surface seal, lime-stabilized cap	Materials/installation	5" (13-cm) lime-stabilized cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.05	5.24	8.04	6.90
Surface seal, PVC membrane cap	Materials/installation	30-mil PVC membrane cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	10.8	9.72	14.4	12.3
Surface seal, soil-cemented cap	Materials/installation	5" (13-cm) soil-cement cap, includes 18" (46-cm) soil cover	$/m^2	Martin 1978	6.05	5.24	8.04	6.90
Surveying	Labor	Labor costs/day	$/day	Moore 1980	220	150	260	230
Tipping fee	Unit costs	Fee paid at secure landfill	$/tonne	SCS 1979	110	110	110	110
Transportation	Labor/equipment	30-ton dump truck/driver, based on one-way hauling distance, return trip included	$/tonne-km	SCS 1981	0.096	0.060	0.128	0.109
Transportation	Labor/equipment	15-ton dump truck/driver, based on one-way hauling distance, return trip included	$/tonne-km	SCS 1981	0.110	0.069	0.145	0.125
Treatment plant	Unit costs	Costs interpolated from Dodge Guide 1980, with SCS estimate	$/l/day	Dodge 1980	0.89	0.70	1.10	1.04
Trench excavation	Labor	16 ft (5 m) deep x 3 ft (1 m) wide, one equipment operator, one laborer	$/m^3	Moore 1980	0.22	0.17	0.35	0.31
Trench excavation	Equipment	16 ft (5 m) deep x 3 ft (1 m) wide, backhoe excavator, sloped 1/2:1	$/m^3	Moore 1980	1.16	1.16	1.16	1.16
Well fittings, 8"	Materials	PVC	$/well	Moore 1980	127	97.8	134.6	119.4
Well fittings, 8"	Installation	PVC	$/well	Moore 1980	98	61.4	120.4	110.7
Well points, 2.5"	Materials/installation	16 ft (4.9 m) long	$/m	Dodge 1980	50.3	40	70	62
Wellpoint fittings	Unit costs	Fittings and accessories	$/well	Dodge 1980	12.0	8.40	14.2	12.5

(Sheet 3 of 3)

TABLE C-6

SURFACE IMPOUNDMENT O&M COST COMPONENTS - METRIC UNITS

Component	Subcomponent	Definition	Metric Units	Source	Source Cost	Low	High	Benchmark
Chemicals	Materials	Wastewater/leachate treatment plant chemicals	$/l/day (influent)	SCS 1980	0.025	0.025	0.025	0.025
Electricity	Power costs	For water treatment plant or extraction, injection, and gas control wells/pumps	$/kwh	SCS 1980	0.05	0.05	0.05	0.05
Refertilizing	Labor/materials	Assume fertilizing once/year	$/m^2	Dodge 1980	0.0060	0.0046	0.0064	0.0056
Grass mowing	Labor/equipment	Assume grass mowing 6 times/year, minimum $10 per visit	$/m^2	Dodge 1980	0.0015	0.00097	0.002	0.0017
Grubbing	Labor/equipment	Assume annual grubbing (clearing) of brush	$/m^2	Dodge 1980	0.19	0.12	0.25	0.22
Maintenance/repair, diversion ditch	Installation	Assume twice annual ditch repair	$/m^3	Means 1980	2.76	1.75	3.63	3.16
Monitoring (analysis)	Laboratory costs	For ground water/leachate monitoring from monitoring wells	$/sample	SCS 1980	330	330	330	330
Monitoring (sampling)	Labor	For ground water/leachate monitoring from monitoring wells	$/hr	SCS 1980	12.5	7.60	16.6	14.2
Operator personnel	Labor	For operation of water treatment plant and sampling for monitoring	$/hr	SCS 1980	12.6	7.02	16.3	14.3

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APPENDIX D

SYMBOLS, ABBREVIATIONS, AND ACRONYMS; METRIC CONVERSION

A	area; activity; slope of saturation vapor pressure curve; acre
a	vegetation parameter
α (alpha)	slope angle
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADS	agricultural drainage standard
AET	actual evapotranspiration
ARS	Agricultural Research Center
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
b	bottom channel width
B_s	channel surface width
C	clay (in the Unified soil classification system); percent of clay-sized material; runoff coefficient; Centigrade (Celsius)
CBR	California Bearing Ratio
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (of 1980)
cc	cubic centimeter
cfs	cubic feet per second
CH	a soil group in the Unified Soil Classification System
CL	a soil group in the Unified Soil Classification System

cm	centimeter
CN	curve number
CPE	chlorinated polyethylene
CRREL	Cold Regions Research and Engineering Laboratory
CSA	Canadian Standards Association
CST	change in soil moisture storage
C_u	Coefficient of Uniformity
Cu	see C_u
cu	cubic
c.y.	cubic yard
D	depth; diameter
d	diameter; depth; angle of repose; thickness of drainage blanket
D_{10}, D_{50}, etc.	diameter of 10-pct-finer, 50-pct-finer, etc., soil particle
DA	Department of the Army
D_d	relative density
δ (delta)	correction for consistent or systematic error of measurement process
δ_m	correction for systematic error due to material composition
δ_p	correction for systematic error due to placement process
δ_q	correction for systematic error due to material quality
δ_t	correction for systematic error due to testing process
dia.	diameter
E	maximum allowable error
e	void ratio; rate at which water impinges on drainage layer; base of natural logarithms; allowable sampling error
e_{max}	maximum void ratio
e_{min}	minimum void ratio

E.O.S.	equivalent opening size
EPA	Environmental Protection Agency
EPDM	ethylene propylene diene monomer
ε (epsilon)	correction for random deviation about the average
F	Fahrenheit; total water infiltrated
f	infiltration capacity
FA	fly ash
F_b	bend factor
f_c	equilibrium infiltration capacity
Fed.	Federal
f_o	initial infiltration capacity
f_1	infiltration capacity one hour after start of excess precipitation
'	foot, feet
ft	foot, feet
G	specific gravity; gravel (in the Unified soil classification system)
g	acceleration of gravity; gram(s)
gal	gallon
γ (gamma)	unit weight
γ_d	dry unit weight, dry density
γ_s	unit weight of solids
γ_t	total unit weight
γ_w	unit weight of water
GC	a soil group in the Unified Soil Classification System
GI	vegetation growth index
GM	a soil group in the Unified Soil Classification System
GP	a soil group in the Unified Soil Classification System
G_s	specific gravity of solids
GW	a soil group in the Unified Soil Classification System

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H	height; high (in the Unified Soil Classification System); horizontal; net daily solar radiation
h	height; head
HCB	hexachlorobenzene
HDPE	high-density polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
h_{max}	height to which water will rise in blanket layer
HP	horsepower
hr	hour
HWS	hazardous waste site
I	rainfall intensity; infiltration
i	hydraulic gradient
I_a	initial abstraction
in.	inch, inches
"	inch, inches
K	hydraulic conductivity; Kelvin (temperature scale)
k	coefficient of permeability; decay constant in exponential equation
kN	kilonewton
K_s	saturated hydraulic conductivity
k_s	saturated permeability of drainage blanket
K_u	unsaturated hydraulic conductivity
L	distance or length; low (in the Unified Soil Classification System); twice the distance between subdrains; albedo
LAI	leaf area index
l	length
lb.	pound
LCFA	lime, cement, fly ash, aggregate
l.f.	linear foot

LFA	lime, fly ash, aggregate
LL	liquid limit
M	silt (in the Unified Soil Classification System)
m	meter
m^2	square meter
max.	maximum
MH	a soil group in the Unified Soil Classification System
MIL	military
mil	(see glossary)
min.	minimum; minute
ML	a soil group in the Unified Soil Classification System
mm	millimeter(s)
MPa	megapascal
mph	miles per hour
μ (mu)	kinematic viscosity; expected or mean value; micro- (= x 10^{-6})
μ_p	expected value or average of many observations recorded for a process
μ_r	true or accepted reference level of a property of material to be measured
n	number of units in a sample; porosity; roughness coefficient (Manning's equation)
NCC	National Climatic Center
NCP	National Contingency Plan
n_e	effective porosity
NR	not recommended
N.T.S.	not to scale
O	organic (in the Unified Soil Classification System)
OH	a soil group in the Unified Soil Classification System
OL	a soil group in the Unified Soil Classification System

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P	poorly graded (in the Unified Soil Classification System); wetted perimeter; precipitation; a numerical exponent
P_{A5}	total 5-day antecedent rainfall
PCA	Portland Cement Association
pcf	pounds per cubic foot
pct	percent
PE	polyethylene
PERC	percolation
PET	potential evapotranspiration
pH	(see glossary)
ϕ (phi)	diameter; angle of internal friction
PI	plasticity index
PL	plastic limit
pls	pure live seed
PSD	pipe slope drain
psf	pounds per square foot
psi	pounds per square inch
Pt	peat (in the Unified Soil Classification System)
PVA	polyvinyl acetate
PVC	polyvinyl chloride
Q	volumetric flow rate
R	hydraulic radius; runoff; incident daily solar radiation
r	radius
RCRA	Resource Conservation and Recovery Act (of 1976)
ρ (rho)	density
RO	surface runoff
R_o	radius of channel bend

S	degree of saturation; sand (in the Unified Soil Classification System); slope; potential retention; available soil moisture storage capacity; capillary suction
s	second
S_b	channel bottom slope
SC	a soil group in the Unified Soil Classification System
SCS	Soil Conservation Service
sec	second
SF	safety factor
s.f.	square foot
σ (sigma)	standard deviation
σ_o	total standard deviation
σ_q	quality standard deviation
σ_t	testing standard deviation
σ^2	variance
σ_m^2	variance due to material composition
σ_o^2	overall variance
σ_p^2	variance due to placement process
σ_q^2	variance due to material quality
σ_t^2	variance due to testing process
σ^1	known or estimated true value of universe or lot standard deviation
SL	shrinkage limit
SM	a soil group in the Unified Soil Classification System; snowmelt
S_o	threshold degree of saturation

SP	a soil group in the Unified Soil Classification System
Spec.	specification
sq.	square
S_s	actual degree of saturation
STD	standard
SW	a soil group in the Unified Soil Classification System
SWMP	Surface Water Management Program or Plan
s.y.	square yard
T	temperature; top channel width
t	time; probability factor, from Student-t tables
t_c	time of concentration
T_p	total soil porosity
t_{sat}	time of saturation
tsf	tons per square foot
USAE	U. S. Army Engineer
USBR	U. S. Bureau of Reclamation
USCE	U. S. Army Corps of Engineers
USCS	Unified Soil Classification System
USDA	U. S. Department of Agriculture; U. S. Department of the Army
USGS	U. S. Geological Survey
V	volume; velocity; vertical
V_g	volume of gas
Vol	volume
V_s	volume of solids
V_v	volume of voids
Vw	volume of water
V'	coefficient of variation

W	weight; well-graded (in the Unified Soil Classification System)
w	water content; width
w_e	effective water content
WES	Waterways Experiment Station
W_l	liquid limit
W_p	plastic limit
W_s	weight of solids; shrinkage limit
wt	weight
W_w	weight of water
X	numerical value of a measurement
X	expected (mean) value of characteristic being measured
y	channel depth
yd	yard
yd^2	square yard(s)
yd^3	cubic yard(s)
Z	reciprocal of tangent of slope angle; number of horizontal units for a vertical rise of one.

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TABLE D-1

METRIC CONVERSION TABLE

Multiply	By	To Obtain
acres	0.4046856	hectares
atmospheres	101.325	kilopascals
cubic feet per second	0.02831685	cubic meters per second
cubic yards	0.7645549	cubic meters
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[a]
feet	0.3048	meters
gallons (U. S. liquid)	3.785412	liters
inches	0.0254	meters
kips (force)	4.448222	kilonewtons
miles (U. S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (mass)	0.4535924	kilograms
tons (short, mass)	907.1847	kilograms
tons (short, mass)	1.102	metric tons (tonnes)

[a]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

9 3 1 2 9 0 4 1 2 7 8

APPENDIX E

GLOSSARY

This glossary is intended to define terms in this Handbook as well as some terms that may be encountered in researching subjects herein. Chief sources for this glossary were the glossaries presented by Lee et al. (1984), Haxo et al. (1980), Hilf (1974c), and Johnson (1981), and definitions in Webster's Third New International Dictionary (G. & C. Merriam Co., 1981). In some cases original definitions were prepared from other sources by the preparers of this Handbook. Where terms are defined by cross-reference, the term specifically defined is not necessarily to be preferred.

9 3 1 2 9 0 4 1 2 7 9

ABSORPTION: A taking up by capillary, osmotic, chemical or solvent action; distinguished from adsorption.

ACID SOIL: A soil with a preponderance of hydrogen ions and probably of aluminum in proportion to hydroxyl ions. Specifically, soil with a pH value less than 7.0. For most practical purposes, a soil with a pH value less than 6.6. The pH values obtained vary greatly with the method used; consequently, there is no unanimous agreement on what constitutes an acid soil. The term is usually applied to the surface layer or to the root zone unless specified otherwise.

ACTIVITY: In clay terminology, a property of clay minerals related to the plasticity of the soils in which they occur.

ADSORPTION: A taking up by physical (physical adsorption) or chemical (chemisorption) forces of the molecules (or ions) of gases, dissolved substances, or liquids by the surfaces of solids or liquids with which they are in contact; distinguished from absorption.

AEOLIAN DEPOSITS: Wind-deposited material such as dune sands and loess deposits.

AERATION, SOIL: The process by which air in the soil is replenished by air from the atmosphere. In a well-aerated soil, the air in the soil is similar in composition to the atmosphere above the soil. Poorly aerated soils usually contain a much higher percentage of carbon dioxide and a correspondingly lower percentage of oxygen. The rate of aeration depends largely on the volume and continuity of pores in the soil.

AGGREGATE: A granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or concrete, or alone as in roadway base courses, railroad ballast, etc.

AIR DRY: The state of dryness (of a soil) at equilibrium with the moisture content in the surrounding atmosphere. The actual moisture content will depend on the relative humidity and the temperature of the surrounding atmosphere.

AIR LANCE: A device used to test, in the field, the integrity of field seams in plastic sheeting. It consists of a wand or tube through which compressed air is blown.

ALKALINE SOIL: A soil that has a pH value greater than 7.0, particularly above 7.3, throughout most or all of the root zone, although the term is commonly applied to only the surface layer or horizon of a soil.

ALLOYS, POLYMERIC: A blend of two or more polymers, e.g., a rubber and a plastic, to improve a given property, e.g., impact strength.

ALLUVIUM: Soil the constituents of which have been transported in suspension by flowing water and subsequently deposited by sedimentation.

AMENDMENT: Any material, such as lime, gypsum, sawdust, or synthetic conditioners, that is worked into the soil to make it more productive. The term is used most commonly for added materials other than fertilizer.

AMPHOTERIC: Having the property of reacting as either an acid or a base. Many oxides and salts have this ability (aluminum hydroxide, for example).

ANCHOR TRENCH: A long narrow ditch on which the edges of a plastic sheet are buried to hold it in place or to anchor the sheet.

ANGLE OF INTERNAL FRICTION: Angle between the abscissa and the tangent of the curve representing the relationship of shear resistance to normal stress acting within a soil.

ANGLE OF REPOSE: Angle between the horizontal and the maximum slope that a soil assumes through natural processes. For dry granular soils the effect of the height of slope is negligible; for cohesive soils the effect of height of slope is so great that the angle of repose is meaningless.

ANION EXCHANGE CAPACITY: The sum total of exchangeable anions that a soil can absorb. Expressed as milliequivalents per 100 gram of soil (or other absorbing materials such as clay).

ANISOTROPIC MASS: A mass having different properties in different directions at any given point.

ANNUAL PLANT: A plant that completes its life cycle in one year or less.

AQUIFER: A water-bearing formation that yields economically significant quantities of ground water.

ARTESIAN: An adjective referring to ground water confined under hydrostatic pressure.

ASH (FIXED SOLIDS): The incombustible material that remains after a fuel or solid waste has been burned.

ASPHALT: A dark-brown to black semisolid cementitious material consisting principally of bitumens which gradually liquefy when heated and which occur in nature as such or are obtained as residue in the refining of petroleum.

ASPHALT CEMENT: A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements and having specified penetration consistency.

ASPHALT MEMBRANE: A relatively thin layer of asphalt formed by spraying a high viscosity, high softening point asphalt cement in two or more applications over the surface to be covered. It is normally 1/4-in. thick and buried to protect it from weathering and mechanical damage.

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ATTERBERG LIMITS: Moisture-content values which are measured for soil materials passing a no. 40 sieve and which define soil plasticity properties. The Atterberg Limits are the Liquid Limit, Plastic Limit, and Shrinkage Limit, q.q.v.

AVAILABLE NUTRIENT: That portion of any element or compound in the soil that readily can be absorbed and assimilated by growing plants. Not to be confused with exchangeable.

AVAILABLE WATER: The portion of water in a soil that can be absorbed by plant roots; usually that water held in the soil against a soil water pressure of up to approximately 15 bars. See Figure 4-5.

BAND SEEDING: Seeding of grasses and legumes in a row one to two inches directly above a band of fertilizer.

BASE COURSE (BASE): In highway construction, a layer of specified or selected material of planned thickness constructed on the subgrade or subbase for the purpose of serving one or more functions such as distributing load, providing drainage, minimizing frost action, etc.

BASE EXCHANGE: The physicochemical process whereby one species of ions adsorbed on soil particles is replaced by another species.

BENTONITE: A rock or natural deposit composed largely of montmorillonite. Because of its swelling and slaking properties it is used in oil-well drilling muds and sealing applications such as slurry trenches.

BERM: A level area which breaks the continuity of a slope, or which forms the shoulder of a road. Also loosely used to mean an embankment with a level top.

BINDER (SOIL): Portion of soil passing No. 40 United States standard sieve.

BIODEGRADABLE: Susceptible to decomposition as a result of attack by microorganisms - said of organic materials.

BITUMEN: A class of black or dark-colored (solid, semisolid, or viscous) cementitious substances, natural or manufactured, composed principally of relatively high-molecular-weight hydrocarbons. Asphalts, tars, pitches, and asphaltites are typical examples of bitumen.

BLOCKING: Unintentional adhesion usually occurring during storage or shipping between plastic films or between a film and another surface.

BLOWN ASPHALT (AIR-BLOWN ASPHALT): Asphalt produced in part by blowing air through it at a high temperature. If a catalyst, e.g., ferric chloride or phosphorus pentoxide, is used in the air-blowing operation, the product is known as catalytically-blown asphalt.

BODIED SOLVENT ADHESIVE: An adhesive consisting of a solution of the liner compound used in the seaming of liner membranes.

BOOT: A bellows-type covering to exclude dust, dirt, moisture, etc., from a flexible joint.

BOULDER: A rock fragment, usually rounded by weathering or abrasion, with an average dimension of 12 inches or more.

BREAKING FACTOR: Tension at break in force per unit of width; units, SI: Newton per meter, customary: pound per inch.

BRUSH MATTING: 1. A matting of branches placed on badly eroded land to conserve moisture and reduce erosion while trees or other vegetative covers are being established. 2. A matting of mesh wire and brush used to retard streambank erosion.

BULKING: The increase in volume of a material due to manipulation. Rock bulks upon being excavated; damp sand bulks if loosely deposited, as by dumping, because the "apparent cohesion" prevents movement of the soil particles to form a reduced volume.

BUNCHGRASS: A grass that does not have rhizomes or stolons and forms a bunch or tuft.

BUTT JOINT: A joint in which the edges of two plates, sheets, etc., to be joined are merely abutted together without overlap.

BUTYL RUBBER: A synthetic rubber based on isobutylene and a minor amount of isoprene. It is vulcanizable and features low permeability to gases and water vapor and good resistance to aging, chemicals, and weathering.

CALCAREOUS SOIL: Soil containing sufficient free calcium carbonate or magnesium carbonate to effervesce carbon dioxide visibly when treated with cold 0.1 normal hydrochloric acid.

CALIFORNIA BEARING RATIO: The ratio of (1) the force per unit area required to penetrate a soil mass with a 3-square-inch circular piston (approximately 2-inch-diameter) at the rate of 0.05 inch per minute to (2) that required for corresponding penetration of a standard material.

CAPILLARY ACTION (CAPILLARITY): The rise or movement of water in the interstices of a soil due to capillary forces.

CAPILLARY FRINGE: The lower subdivision of the zone of aeration, immediately above the water table, in which the interstices are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by surface tension. Its upper boundary with the intermediate belt is indistinct but is sometimes defined arbitrarily as the level at which 50 percent of the interstices are filled with water.

CAPILLARY HEAD: The potential, expressed in head of water, that causes the water to flow by capillary action.

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CAPILLARY MIGRATION (CAPILLARY FLOW): The movement of water by capillary action.

CAPILLARY PRESSURE: The difference in pressure across the interface between two immiscible fluid phases jointly occupying the interstices of a rock. It is due to the tension of the interfacial surface, and its value depends on the curvature of that surface.

CAPILLARY RISE (HEIGHT OF CAPILLARY RISE): The height above a free water elevation to which water will rise by capillary action.

CATION EXCHANGE CAPACITY (BASE EXCHANGE CAPACITY): A measure of the extent to which the cations in a soil (adsorbed on mineral surfaces; within the crystal framework of some mineral species; and within certain organic compounds) can be reversibly replaced by those of salt solutions and acids. Usually expressed in meq. (milliequivalents) per 100 grams of soil.

CELL: Portion of waste in a landfill which is isolated horizontally and vertically from other portions of waste in the landfill by means of soil barrier.

CHEMICAL FIXATION: Treatment process which involves reactions between the waste and certain chemicals, and which results in solids which encapsulate, immobilize or otherwise tie up hazardous components in the waste so as to minimize the leaching of hazardous components and render the waste nonhazardous or more suitable for disposal.

CHLORINATED POLYETHYLENE (CPE): Family of polymers produced by chemical reaction of chlorine on the linear backbone chain of polyethylene. The resultant rubbery thermoplastic elastomers presently contain 25-45% chlorine by weight and 0-25% crystallinity. CPE can be vulcanized but is usually used in a nonvulcanized form.

CHLOROSULFONATED POLYETHYLENE (CSPE): Family of polymers that are produced by polyethylene reacting with chlorine and sulfur dioxide. Present polymers contain 25-43% chlorine and 1.0-1.4% sulfur. They are used in both vulcanized and nonvulcanized forms. Most membranes based on CSPE are nonvulcanized. ASTM designation for this polymer is CSM.

CHUTE: A high-velocity, open channel for conveying water to a lower level without erosion.

CLAY (CLAY SOIL): Fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and which exhibits considerable strength when air-dry.

CLAY MINERALS: Naturally occurring hydrous aluminosilicate minerals with a planar or sheetlike crystal structure (known as phyllosilicates), formed in nature by weathering or hydrothermal action, always very fine-grained, usually occurring in earthy masses. Positive identification of clay minerals usually requires a combination of optical, x-ray, chemical and/or physical tests.

CLAYPAN: A dense, compact layer in the subsoil having a much higher clay content than the overlying material from which it is separated by a sharply defined boundary; formed by downward movement of clay or by synthesis of clay in place during soil formation.

CLAY SIZE: Grain sizer finer than 0.002 mm. (0.005 mm. in some cases). See discussion in Sec. 3.2.2, and Figure 3-3.

COAL TAR: Tar produced by the destructive distillation of bituminous coal.

COATED FABRIC: Fabrics which have been impregnated and/or coated with a plastic material in the form of a solution, dispersion, hotmelt, or powder. The term also applies to materials resulting from the application of a preformed film to a fabric by means of calendering.

COBBLE: A rock fragment usually rounded or semirounded with an average dimension between 3 and 12 inches.

COEFFICIENT OF COMPRESSIBILITY (COEFFICIENT OF COMPRESSION): The secant slope, for a given pressure increment, of the pressure/void-ratio curve.

COEFFICIENT OF INTERNAL FRICTION: The tangent of the angle of internal friction (see Internal Friction).

COEFFICIENT OF PERMEABILITY: The rate of discharge of water under laminar-flow conditions and at a standard temperature (usually 20°C) through a unit cross-sectional area of a porous medium under a unit hydraulic gradient. Frequently simply termed "permeability" in soil-mechanics usage. See "Permeability."

COEFFICIENT OF UNIFORMITY: The ratio D_{60}/D_{10}, where D_{60} is the particle diameter corresponding to 60 percent finer on the grain-size curve, and D_{10} is the particle diameter corresponding to 10 percent finer on the grain-size curve.

COHESION: That part of soil strength that is present independently of any applied pressures, either mechanical or capillary, and would remain, though not necessarily permanently, if all applied pressures were removed. Indicated by the term C in the Coulomb equation: $S = C + \bar{\sigma} \tan \phi$.

COHESIONLESS SOIL: A soil that when unconfined has little or no strength when air-dried, and that has little or no cohesion when submerged.

COHESIVE SOIL: A soil that when unconfined has considerable strength when air-dried, and that has significant cohesion when submerged.

COLLOID: In soil, organic or inorganic matter having very small particle size and a correspondingly large specific surface. In general, colloidal particles are too small to be seen with the ordinary compound microscope, and remain indefinitely in a suspension rather than settling out.

COMPACTION: The densification of a soil by means of mechanical manipulation.

COMPACTION CURVE (PROCTOR CURVE) (MOISTURE-DENSITY CURVE): The curve showing the relationship between the dry unit weight (density) and the water content of a soil for a given compactive effort.

COMPACTION TEST (MOISTURE-DENSITY TEST): A laboratory compacting procedure whereby a soil at a known water content is placed in a specified manner into a mold of given dimensions, subjected to a compactive effort of controlled magnitude, and the resulting unit weight determined. The procedure is repeated for various water contents sufficient to establish a relation between water content and unit weight.

COMPANION CROP: Seeding of a short-life crop with the permanent species to aid in erosion control until the permanent species are established.

COMPRESSIBILITY: Property of a soil pertaining to its susceptibility to decrease in volume when subjected to load.

COMPRESSIVE STRENGTH (UNCONFINED COMPRESSIVE STRENGTH): The load per unit area at which an unconfined prismatic or cylindrical specimen of soil will fail in a simple compression test.

CONSISTENCY: The relative ease with which a soil can be deformed.

CONSOLIDATED DRAINED TEST (SLOW TEST): A soil test in which essentially complete consolidation under the confining pressure is followed by additional axial (or shear) stress applied in such a manner that even a fully saturated soil of low permeability can adapt itself completely (fully consolidate) to the changes in stress due to the additional axial (or shear) stress.

CONSOLIDATED UNDRAINED TEST (CONSOLIDATED QUICK TEST): A test in which complete consolidation under the vertical load (in a direct shear test) or under the confining pressure (in a triaxial test) is followed by a shear at constant water content.

CONSOLIDATION TEST: A test in which the specimen is laterally confined in a ring and is compressed between porous plates.

CONSOLIDATION-TIME CURVE (TIME CURVE) (CONSOLIDATION CURVE) (THEORETICAL TIME CURVE): A curve that shows the relation between (1) the degree of consolidation and (2) the elapsed time after the application of a given increment of load.

CONTOUR: 1. An imaginary line on the surface of the earth connecting points of the same elevation. 2. A line drawn on a map connecting points of the same elevation.

COOL-SEASON PLANT: A plant that makes its major growth during the cool portion of the year, primarily in the spring but in some localities in the winter.

COURSE: See "Lift."

COVER, FINAL: The cover material that is applied at the end of the useful life of a disposal site and represents the permanently exposed final surface of the fill.

COVER MATERIAL: A soil or other suitable material that is used to cover the liner or wastes in a disposal site.

CROSSLINKING: A general term referring to the formation of chemical bonds between polymeric chains to yield an insoluble, three-dimensional polymeric structure. Crosslinking of rubbers is vulcanization, q.v.

CRITICAL POINT: (Physical Chemistry) For a given substance, temperature and pressure above which no meniscus can form, so that liquid and gaseous phases become indistinguishable.

CULTIVAR: An assemblage of cultivated plants which is clearly distinguished by its characters (morphological, physiological, cytological, chemical, or others) and which when reproduced (sexually or asexually), retains those distinguishing characters. The terms "cultivar" and "variety" are equivalents.

CURING: See "Vulcanization."

CUT: Portion of land surface or area from which earth has been removed or will be removed by excavation; the depth below original ground surface to excavated surface.

CUTBACK ASPHALT: Asphalt cement that has been liquefied by blending with petroleum solvents which are in this context also called diluents. Upon exposure to atmospheric conditions the diluents evaporate leaving the asphalt cement to perform its function.

CUT-OFF TRENCH: A trench that is filled with material that may be impermeable or very permeable to the flow of a gas or water. The barrier is used to prevent the movement of gas or water or to intercept them and to direct them to another location.

DEFORMATION: Change in shape.

DEGREE OF SATURATION: See "Percent Saturation."

DENSITY: (in Soil Mechanics) see Unit Weight.

DIKE: A barrier to the flow of surface waters. It may be a raised embankment or a ditch.

DILATANCY: (in Soil Mechanics) The volume change of cohesionless soils when subject to shear deformation.

DISPERSION, SOIL: The breaking down of soil aggregates into individual particles, resulting in single-grain structure. Ease of dispersion is an important factor influencing the erodibility of soils. Generally speaking, the more easily dispersed the soil, the more erodible it is.

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DISPERSIVITY: Tendency toward dispersion.

DIVERSION DAM: A barrier built to divert part or all of the water from a stream into a different course.

DOUBLE LAYER (ELECTRICAL DOUBLE LAYER, DIFFUSE DOUBLE LAYER): In colloid chemistry, the electric charges on the surface of the disperse phase (usually negative), and the adjacent diffuse layer (usually positive) of ions in solution.

DRILL SEEDING: Planting seed with a drill in relatively narrow rows, generally less than a foot apart.

EDAPHIC FACTOR: A condition or characteristic of the soil (chemical, physical, or biological) which influences organisms.

EFFECTIVE DIAMETER (EFFECTIVE SIZE): Particle diameter corresponding to 10 percent finer on the grain-size curve.

EFFLUENT: A liquid which flows out of a containing space.

ELASTICITY: The capability of a strained body to recover its size and shape after deformation.

ELASTOMER: See "Rubber."

ELEVATION HEAD: Head possessed by an element of water by virtue of its elevation with respect to a level datum plane. May be positive or negative. Expressed in linear units (e.g. feet), representing vertical distance from datum.

ELONGATION: See "Ultimate Elongation."

EMULSIFIED ASPHALT: A mixture of asphalt and water in which the asphalt is held in suspension in the water by an emulsifying agent. Emulsified asphalts may be either cationic or anionic depending on the emulsifying agent used.

EPDM: A synthetic elastomer based on ethylene, propylene, and a small amount of a nonconjugated diene to provide sites for vulcanization. EPDM features excellent heat, ozone and weathering resistance, and low-temperature flexibility.

EPHEMERAL STREAM: A stream or portion of a stream that flows only in direct response to precipitation, and receives little or no water from springs or no long-continued supply from snow or other sources, and its channel is at all times above the water table.

EPICHLOROHYDRIN RUBBER: This synthetic rubber includes two epichlorohydrin-based elastomers which are saturated, high-molecular-weight, aliphatic polyethers with chloro-methyl side chains. The two types include a homopolymer (CO) and a copolymer of epichlorohydrin and ethylene oxide (ECO).

These rubbers are vulcanized with a variety of reagents that react difunctionally with the chloromethyl group; including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

EROSION: 1. The wearing away of a land surface by moving water, wind, ice, or other geological agents, including such processes as gravitational creep. 2. Detachment and movement of soil or rock fragments by water, wind, ice, or gravity.

ESSENTIAL ELEMENT (PLANT NUTRITION): A chemical element required for the normal growth of plants.

EVA: Family of copolymers of ethylene and vinyl acetate used for adhesives and thermoplastic modifiers. They possess a wide range of melt indexes.

EXCHANGE CAPACITY: See "Cation exchange capacity."

EXCHANGEABLE NUTRIENT: A plant nutrient that is held by the adsorption complex of the soil and is easily exchanged with the anion or cation of neutral salt solutions.

EXPOSURE: Direction of slope with respect to points of a compass.

EXTRUDER: A machine with a driven screw for continuous forming of rubber by forcing through a die; can be used to manufacture films and sheeting.

FERTILITY (SOIL): The quality of a soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants when other growth factors, such as light, moisture, temperature, and the physical condition of the soil, are favorable.

FERTILIZER FORMULA: The quantity and grade of the crude stock materials used in making a fertilizer mixture; for example, one formula for a fertilizer with an analysis of 5-10-5 could be 625 pounds of 16 percent nitrate of soda, 1,111 pounds of 18 percent superphosphate, 200 pounds of 50 percent muriate of potash, and 64 pounds of filler per ton.

FIELD CAPACITY: The maximum amount of moisture a soil or solid waste can retain in a gravitational field without a continuous downward percolation.

FILM: (Polymeric technology) Sheeting having nominal thickness not greater than 10 mils.

FILTER (PROTECTIVE FILTER): A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles due to flowing water.

FINES: Portion of soil finer than a No. 200 United States standard sieve.

FLOC: Loose, open-structured mass formed in a suspension by the aggregation of minute particles.

FLOCCULATION: The process of forming flocs.

FLOCCULENT: Containing, consisting of, or occurring in the form of loosely aggregated particles or soft flakes; made up of flocs.

FLORA: The sum total of the types of plants in an area at one time.

FLOW CHANNEL: The portion of a flow net bounded by two adjacent flow lines; any channel through which a fluid may flow.

FLOW LINE: The path that a particle of water follows in its course of seepage under laminar flow conditions.

FLOW NET: A graphical representation of flow lines and equipotential lines used in the study of seepage phenomena.

FLUX: (fluid flow) flow concentration: volumetric flow rate divided by area.

FLY ASH: Fine solid particles of noncombustible ash carried out of a bed of solid fuel by the combustion draft and either deposited in quiet spots in furnaces or flues or carried up the stack.

FOOTING: Portion of the foundation of a structure that transmits loads directly to the soil.

FORB: A herbaceous plant which is not a grass, sedge, or rush. A broadleaf herb or weed.

FREE WATER (GRAVITATIONAL WATER) (GROUND WATER) (PHREATIC WATER): Water that is free to move through a soil mass under the influence of gravity.

FREE WATER ELEVATION (see WATER TABLE)

FROST ACTION: Freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.

FROST HEAVE: The raising of a surface due to the accumulation of ice in the underlying soil.

FUNGI: Simple plants that lack a photosynthetic pigment.

GABION: A rectangular or cylindrical wire mesh cage filled with rock and used as a protecting apron, revetment, etc., against erosion.

GEOMEMBRANE: A flexible, impervious, thin sheet of rubber or plastic material used primarily for linings and covers of liquid or solid storage impoundments, thus serving as a moisture barrier.

GEOTEXTILE: A flexible, porous (to water flow), synthetic fabric used in soil construction for applications such as separation, reinforcement, filtration, or drainage.

GLACIAL TILL (TILL): Material deposited by glaciation, usually composed of a wide range of particle sizes, which has not been subjected to the sorting action of water.

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GRADATION (GRAIN-SIZE DISTRIBUTION) (PARTICLE-SIZE DISTRIBUTION) (SOIL TEXTURE): Proportion of material of each grain size present in a given soil.

GRADE: 1. The slope of a road, channel, or natural ground. 2. The finished surface of a canal bed, roadbed, top of embankment, or bottom of excavation; any surface prepared for the support of construction like paving or laying a conduit. 3. To finish the surface of a canal bed, roadbed, top of embankment, or bottom of excavation.

GRADIENT: The degree of slope or a rate of change of a parameter measured over distance.

GRAIN SIZE ANALYSIS (MECHANICAL ANALYSIS): The process of determining gradation of soil.

GRAVEL: Unconsolidated granular mineral material of pebble sizes; rounded or semirounded particles of rock that will pass a 3-inch and be retained on a No. 4 United States standard sieve. See Figure 3-3.

GRAVITATIONAL WATER: Water which moves into, through, or out of the soil under the influence of gravity.

GROUND COVER: Grasses or other plants grown to keep soil from being blown or washed away.

GROUND WATER, CONFINED: (see ARTESIAN)

GROUND WATER, PERCHED: Unconfined ground water separated from an underlying body of ground water by an unsaturated zone. Its water table is a perched water table. It is held up by a perching bed whose permeability is so low that water percolating downward through it is not able to bring water in the underlying unsaturated zone above atmospheric pressure. Perched ground water may be either permanent, where recharge is frequent enough to maintain a saturated zone above the perching bed, or temporary, where intermittent recharge is not great or frequent enough to prevent the perched water from disappearing from time to time as a result of drainage over the edge of or through the perching bed.

GROUND WATER, UNCONFINED: Water in an aquifer that has a water table.

GROUT: A cementing or sealing mixture which may be injected, poured, or otherwise introduced into a confined or unconfined space in a fluid condition, and which after introduction sets up to perform its cementing or sealing function.

GROWING SEASON: The period and/or number of days between the last freeze in the spring and the first frost in the fall for the freeze threshold temperature of the crop or other designated temperature threshold.

GULLY: A channel or miniature valley cut by concentrated runoff but through which water commonly flows only during and immediately after heavy rains or during the melting of snow; may be dendritic or branching or it may be linear,

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rather long, narrow, and of uniform width. The distinction between gully and rill is one of depth. A gully is sufficiently deep that it would not be obliterated by normal tillage operations, whereas a rill is of lesser depth and would be smoothed by ordinary farm tillage.

HALOPHYTE: A plant adapted to existence in a saline environment.

HARDPAN: A hardened soil layer in the lower A or in the B horizon caused by cementation of soil particles with organic matter or with materials such as silica, sesquioxides, or calcium carbonate. The hardness does not change appreciably with changes in the moisture content, and pieces of the hard layer do not slake in water.

HAZARDOUS WASTE: A solid waste or combination of solid wastes, which because of its quantity, concentration or physical, chemical, or infectious characteristics may:

A. Cause, or significantly contribute to an increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness; or

B. Pose a substantial present or potential hazard to human health or the environment when improperly treated, stored, transported, or disposed of, or otherwise managed (Public Law 94-580, 1976).

HEAD: A measure of the energy that water possesses by virtue of its elevation, pressure, or velocity. The components Elevation Head, Pressure Head, and Velocity Head (q.q.v.) combine to make Total Head. All heads are expressed in linear units, e.g. feet. See also Static Head. At all points in a body of water at rest, the total head (equals static head) is the same, pressure heads exactly compensating elevation heads, and velocity heads being zero. Water flows spontaneously from points of higher to points of lower total head.

HEAT SEAMING: The process of joining two or more thermoplastic films or sheets by heating areas in contact with each other to the temperature at which fusion occurs.

HEAVE: Upward movement of soil caused by expansion or displacement resulting from phenomena such as: moisture absorption, removal of overburden, driving of piles, and frost action.

HEAVY METALS: Any of the metals that react readily with dithizone. They include bismuth, cadmium, cobalt, chromium, copper, gold, iron, manganese, mercury, nickel, lead, and zinc.

HERB: Any flowering plant except those developing persistent woody bases and stems above the ground.

HORIZON (SOIL HORIZON): One of the layers of the soil profile, distinguished principally by its texture, color, structure, and chemical content.

A HORIZON: The uppermost layer of a soil profile from which inorganic colloids and other soluble materials have been leached. Usually contains remnants of organic life.

B HORIZON: The layer of a soil profile in which material leached from the overlying A horizon is accumulated.

C HORIZON: Undisturbed parent material from which the overlying soil profile has been developed.

HUMUS: A brown or black material formed by the partial decomposition of vegetable or animal matter; the organic portion of soil.

HYDRAULIC ASPHALT CONCRETE: Similar to asphalt concrete designed for roadway paving, except that it has a higher mineral filler and asphalt content in order to insure an essentially voidless mix after compaction.

HYDRAULIC CONDUCTIVITY: Term used in ground-water hydrology and soil science. Equivalent to Coefficient of Permeability, q.v.

HYDRAULIC GRADIENT: The loss of hydraulic head per unit distance of flow, $\frac{dh}{dL}$.

HYDROSTATIC PRESSURE: The pressure in a liquid under static conditions; the product of the unit weight of the liquid and the difference in elevation between the given point and the free water elevation.

HYDROPHYTE: A plant that grows in water or in wet or saturated soils.

HYGROSCOPIC CAPACITY (HYGROSCOPIC COEFFICIENT): Ratio of (1) the weight of water absorbed by a dry soil in a saturated atmosphere at a given temperature to (2) the weight of the oven-dried soil.

HYGROSCOPIC WATER CONTENT: The water content of an air-dried soil.

ILLITE: A very common clay mineral of uncertain specificity also termed "hydrous mica" or "clay mica," of moderate specific surface and fairly low exchange capacity, rarely if ever found pure.

IMPERMEABLE: Not permitting passage of a fluid or a gas through its substance.

IMPERVIOUS: See "Impermeable."

IMPOUNDMENT: See "Surface Impoundment."

IN SITU: In its natural or original position.

INDICATOR PLANTS: Plants characteristic of specific soil or site conditions.

INDUSTRIAL WASTE: Waste from industrial processes as distinct from municipal solid waste.

INFILTRATION: The downward entry of water into the soil.

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INFILTRATION RATE (INFILTRATION CAPACITY): A soil characteristic determining the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water. It has the dimensions of velocity.

INFILTRATION VELOCITY: The actual rate at which water is entering the soil at any given time. It may be less than the maximum (the infiltration rate) because of a limited supply of water (rainfall or irrigation). It has the same units as infiltration rate.

INOCULATION: The process of introducing pure or mixed cultures of microorganisms into natural or artificial culture media.

INTERCEPTOR DRAIN: Surface or subsurface drain, or a combination of both, designed and installed to intercept flowing water.

INTERNAL FRICTION: The portion of the shear strength of a soil indicated by the terms $p \tan \phi$ in Coulomb's equation $s = c + p \tan \phi$. It is usually considered to be due to the interlocking of the soil grains and the resistance to sliding between the grains.

INTERSEEDING: Seeding into an established vegetation.

INTERSTICE: An opening or space between one thing and another, as an opening in a rock or soil that is not occupied by solid matter. Synonyms = void, pore.

INTRINSIC PERMEABILITY: A measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement (assuming no alteration of the medium by the liquid). It is dependent upon the shape and size of the pores.

INVADER PLANT SPECIES: Plant species that were absent in undisturbed portions of the original plant community and will invade under disturbance or continued overuse. Commonly termed invaders.

ISOTROPIC MASS: A mass having the same property (or properties) in all directions.

JULIAN DATE: In common usage, e.g., military and computer, the calendar date expressed as a series of digits, sequenced throughout the year. Commonly, four digits of which the first represents the year, the last three the day, e.g., 9364 is December 30, 1979 (or 1969, 1989, ...).

KAOLIN: A variety of clay containing a high percentage of kaolinite.

KAOLINITE: A common clay mineral of relatively simple and constant chemistry and low specific surface, activity, and exchange capacity.

LAMINAR FLOW (STREAMLINE FLOW) (VISCOUS FLOW): Flow in which each fluid particle moves in a direction parallel to every other particle, and in which the head loss is proportional to the first power of the velocity.

LANGLEY: A unit of solar radiation equivalent to one gram calorie per square centimeter of irradiated surface.

LAPPED JOINT: A joint made by placing one surface to be joined partly over another surface and bonding the overlapping portions.

LEACHATE: Liquid that has percolated through or drained from a material and contains soluble, partially soluble, or miscible components removed from such material.

LEACHED SOIL: A soil from which most of the soluble materials ($CaCO_3$ and $MgCO_3$ and more soluble materials) have been removed from the entire profile or have been removed from one part of the profile and have accumulated in another part.

LEACHING: The removal from the soil in solution of the more soluble materials by percolating waters.

LEGUME: A member of the pulse family. Includes many valuable food and forage species, such as peas, beans, peanuts, clovers, alfalfas, sweet clovers, lespedezas, vetches, and kudzu. Practically all legumes are nitrogen-fixing plants.

LEGUME INOCULATION: The addition of nitrogen-fixing bacteria to legume seed or to the soil in which the seed is to be planted.

LIFT: A single layer of compacted soil. Lift thickness depends on soil and degree of compaction needed (also termed "course").

LIME: From the strictly chemical standpoint, refers to only one compound, calcium oxide (CaO); however, the term is commonly used in agriculture to include a great variety of materials that are usually composed of the oxide, hydroxide, or carbonate of calcium or of calcium and magnesium; used to furnish calcium and magnesium as essential elements for the growth of plants and to neutralize soil acidity. The most commonly used forms of agricultural lime are ground limestone (carbonates), hydrated lime (hydroxides), burnt lime (oxides), marl, and oyster shells.

LINEAR EXPANSION: The increase in one dimension of a soil mass, expressed as a percentage of that dimension at the shrinkage limit, when the water content is increased from the shrinkage limit to any given water content.

LINEAR SHRINKAGE: Decrease in one dimension of a soil mass, expressed as a percentage of the original dimension, when the water content is reduced from a given value to the shrinkage limit.

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LINER: A layer of emplaced material beneath a surface impoundment or landfill which is intended to restrict the escape of waste or its constituents from the impoundment or landfill. May include: reworked or compacted soil and clay, asphaltic and concrete materials, spray-on membranes, polymeric membranes, chemisorptive substances, or any substance that serves the above stated purpose.

LIQUID LIMIT: (1) The water content corresponding to the arbitrary limit between the liquid and plastic states of consistency of a soil. (2) The water content at which a pat of soil, cut by a groove of standard dimensions, will flow together for a distance of one-half inch under the impact of 25 blows in a standard liquid limit apparatus.

LOAM: A mixture of sand, silt, or clay, or a combination of any of these, with organic matter (humus). It is sometimes called topsoil in contrast to the subsoils that contain little or no organic matter. A textural name for soils of certain gradations in the agricultural system.

LOESS: A uniform aeolian deposit of silty material having an open structure and relatively high cohesion due to cementation of clay or calcareous material at grain contacts. A characteristic of loess deposits is that they can stand with nearly vertical slopes. Loess has high vertical permeability.

LYSIMETER: A device used to measure the quantity or rate of water movement through or from a block of soil or other material, such as solid waste, or used to collect percolated water for qualitative analysis.

MACRONUTRIENT: A chemical element necessary in large amounts (always greater than one part per million) for the growth of plants; usually applied artificially in fertilizer or liming materials. "Macro" refers to quantity and not the essentiality of the element. Examples are nitrogen, phosphorus, potassium and calcium. See micronutrient.

MACROORGANISMS: Those organisms retained on a U. S. standard sieve no. 30 (openings of 0.589 mm); those organisms visible to the unaided eye. See microorganisms.

MASTIC: A mixture of mineral aggregate, mineral filler, and asphalt in such proportions that the mix can be applied hot by pouring or by mechanical manipulation; it forms a voidless mass without being compacted.

MECHANICAL ANALYSIS: See "Grain Size Analysis."

MESOPHYTE: A plant that grows under intermediate moisture conditions.

MICROCLIMATE: 1. The climatic condition of a small area resulting from the modification of the general climatic conditions by local differences in elevation or exposure. 2. The sequence of atmospheric changes within a very small region.

MICRONUTRIENT: A chemical element necessary in only extremely small amounts for the growth of plants. "Micro" refers to the amount used rather than to its essentiality. Examples are boron, chlorine, copper, iron, manganese, and zinc. See macronutrient.

MICROORGANISMS: Those organisms retained on a U. S. standard sieve no. 100 (openings of 0.149 mm); those minute organisms invisible or only barely visible to the unaided eye. See macroorganisms.

MIL: Unit of length, equal to .001 inch or .0254 mm.

MINERAL FILLER: A finely divided mineral product of which at least 65% will pass a No. 200 sieve which has a sieve opening of 74 µm. Pulverized limestone is the most common manufactured filler, although other stone dust, silica, hydrated lime, portland cement, and certain natural deposits of finely divided matter are also used.

MODULUS OF ELASTICITY (MODULUS OF DEFORMATION): The ratio of stress to strain for a material under given loading conditions; numerically equal to the slope of the tangent or the secant of a stress-strain curve.

MOISTURE CONTENT: See "Water Content."

MONITORING: All procedures used to systematically inspect and collect data on operational parameters of a facility or on the quality of the air, ground water, surface water or soil.

MONITORING WELL: A well used to obtain water samples for water quality analysis or to measure ground-water levels.

MONTMORILLONITE: A common clay mineral of complex and variable chemistry, high to extremely high specific surface and activity, and high exchange capacity. Montmorillonite is the essential component of bentonite, q.v. A general group term proposed for montmorillonite-like minerals is "smectite." Montmorillonites swell by absorbing water within their crystal lattice, leading to variable interlayer spacing.

MUCK: An organic soil of very soft consistency.

MULCH: A natural or artificial layer of plant residue or other materials, such as sand or paper, on the soil surface.

MUNICIPAL SOLID WASTE: Solid waste collected from residential and commercial sources in bins and other large containers.

NATIVE SPECIES: A species that is part of an area's original fauna or flora.

NATURAL REVEGETATION: Natural reestablishment of plants; propagation of new plants over an area by natural processes.

NEOPRENE (POLYCHLOROPRENE): Generic name for a synthetic rubber based primarily on chloroprene, i.e. chlorobutadiene. Vulcanized generally with metal oxide. Resistant to ozone and aging and to some oils.

NITRILE RUBBER: A family of copolymers of butadiene and acrylonitrile that can be vulcanized into tough, oil-resistant compounds. Blends with PVC are used where ozone and weathering are important requirements in addition to its inherent oil and fuel resistance.

NITROGEN-FIXING PLANT: A plant that can assimilate and fix the free nitrogen of the atmosphere with the aid of bacteria living in the root nodules. Legumes with the associated rhizobium bacterial in the root nodules are the most important nitrogen-fixing plants.

NORMALLY CONSOLIDATED SOIL DEPOSIT: A soil deposit that has never been subjected to a pressure greater than the existing overburden pressure.

NOXIOUS SPECIES: A plant that is undesirable because it conflicts, restricts, or otherwise causes problems under the management objectives. Not to be confused with species declared noxious by laws.

NUTRIENTS: 1. Elements, or compounds, essential as raw materials for organism growth and development, such as carbon, oxygen, nitrogen, phosphorus, etc.
2. The dissolved solids and gases of the water of an area.

OPTIMUM MOISTURE CONTENT (OPTIMUM WATER CONTENT): The water content at which a soil can be compacted to the maximum dry unit weight by a given compactive effort.

ORGANIC SOIL: Soil with a high organic content. In general, organic soils are very compressible and have poor load-sustaining properties.

OVENDRY SOIL: Soil which has been dried at 105°C until it reaches a constant weight.

OVERCONSOLIDATED SOIL DEPOSIT: A soil deposit that has been subjected to pressure greater than the present overburden pressure.

PAN: Horizon or layer in soil that is strongly compacted, indurated, or very high in clay content, e.g., claypan, fragipan, hardpan.

PARENT MATERIAL: Material from which a soil has been derived.

PARTICLE SIZE: The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods.

PARTICLE SIZE DISTRIBUTION: See "Gradation."

PEAT: A fibrous mass of organic matter in various stages of decomposition, generally dark brown to black in color and of spongy consistency.

PEBBLE: Rock particle, commonly rounded from natural abrasion, of a size larger than sand and smaller than cobbles, thus approximately 3 to 75 mm.

PERCENT SATURATION: The ratio, expressed as a percentage, of (1) the volume of water in a given soil mass to (2) the total volume of intergranular space (voids).

PERCHED WATER TABLE: A water table usually of limited area maintained above the normal free water elevation by the presence of an intervening relatively impervious confining stratum.

PERCOLATION: Downward movement of water through soil. Especially, the downward flow of water in saturated or near-saturated soil at hydraulic gradients of the order of 1.0 or less.

PERENNIAL PLANT: A plant that normally lives three or more years.

PERMEABILITY: Capability of a material to transmit fluid through its substance. See "Coefficient of Permeability," "Hydraulic Conductivity," and "Intrinsic Permeability."

PESTICIDE: Chemical agent used to kill animal and vegetable life which interferes with agricultural productivity.

pH: Logarithm of the reciprocal of the hydrogen ion concentration in water or an aqueous solution. Neutral is pH 7.0. All pH values below 7.0 are acid, and all above 7.0 are alkaline or basic.

PHASE: A homogeneous part of a chemical system, separated from other parts by physical boundaries.

PHREATOPHYTE: A plant deriving its water from subsurface sources; commonly used to describe nonbeneficial, water-loving vegetation.

PIEZOMETER: An instrument for measuring pressure head.

PIPING: The movement of soil particles by percolating or seeping water leading to the development of channels and internal erosion.

PLANT SUCCESSION: The process of vegetation development whereby an area becomes successively occupied by different plant communities of higher ecological order.

PLANTING SEASON: The period of the year when planting or transplanting is considered advisable from the standpoint of successful establishment.

PLASTIC FLOW (PLASTIC DEFORMATION): The deformation of a plastic material beyond the point of recovery, accompanied by continuing deformation with no further increase in stress.

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PLASTIC LIMIT: (1) The water content corresponding to an arbitrary limit between the plastic and the semisolid states of consistency of a soil. (2) Water content at which a soil will just begin to crumble when rolled into a thread approximately one-eighth inch in diameter.

PLASTIC STATE (PLASTIC RANGE): The range of consistency within which a soil exhibits plastic properties.

PLASTICITY: The property of a soil which allows it to be deformed beyond the point of recovery without cracking or appreciable volume change.

PLASTICITY INDEX: Numerical difference between the liquid limit and the plastic limit.

PLASTICIZER: A plasticizer is a material, frequently "solvent-like," incorporated in a plastic or a rubber to increase its ease of workability, its flexibility, or extensibility. Adding the plasticizer may lower the melt viscosity, the temperature of the second order transition, or the elastic modulus of the polymer. Plasticizers may be monomeric liquids (phthalate esters), low molecular weight liquid polymers (polyesters) or rubbery high polymers (E/VA). The most important use of plasticizers is with PVC where the choice of plasticizer will dictate under what conditions the liner may be used.

POLYESTER FIBER: Generic name for a manufactured fiber in which the fiber-forming substance is any long chain synthetic polymer composed of an ester of a dihydric alcohol and terephthalic acid. Scrims made of polyester fiber are used for fabric reinforcement.

POLYMER: A macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high molecular weight polymers.

POLYMERIC LINER: Plastic or rubber sheeting used to line disposal sites, pits, ponds, lagoons, canals, etc.

POLYVINYL CHLORIDE (PVC): A synthetic thermoplastic polymer prepared from vinylchloride. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens; flexible forms used in manufacture of sheeting.

PORE: A small to minute opening or passageway in a rock or soil; an interstice.

POROSITY: The ratio, usually expressed as a percentage, of (1) the volume of voids of a given soil mass to (2) the total volume of the soil mass.

PORTLAND CEMENT: A hydraulic cement made by burning and grinding a mixture of calcareous and argillaceous materials, e.g., limestone and clay.

PRESSURE: Intensity of loading. The load divided by the area over which it acts. A scalar quantity. Cf. "stress."

PRESSURE HEAD: Head possessed by an element of water by virtue of its pressure. Expressed in linear units (e.g. feet). Equal to the depth below a free surface that would produce the existing pressure under static conditions.

PRESSURE/VOID-RATIO CURVE: A curve representing the relationship between pressure and void ratio of a soil as obtained from a consolidation test.

PRINCIPAL PLANE: Each of three mutually perpendicular planes through a point in a solid mass on which the shearing stress is zero.

PROCTOR COMPACTION CURVE: See "Compaction Curve."

PUNCTURE RESISTANCE: Extent to which a material is able to withstand the action of a sharp object without perforation.

QUICK TEST: See "Unconsolidated Undrained Test."

RELATIVE DENSITY: The ratio of (1) the difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio to (2) the difference between its void ratios in the loosest and in the densest states.

REMOLDED SOIL: Soil that has had its natural structure modified by manipulation.

RESIDUAL SOIL: Soil derived in place by weathering of the underlying material.

REVEGETATION: Plants or growth that replaces original ground cover following land disturbance.

RHIZOME: A horizontal underground stem, usually sending out roots and aboveground shoots at the nodes.

RIPRAP: Broken rock, cobbles, or boulders placed on earth surfaces, such as the face of a dam or the bank of a stream, for protection against the action of water (waves); also applied to brush or pole mattresses, or brush and stone, or other similar materials used for soil erosion control.

ROCK FLOUR: See "Silt."

ROLL GOODS: A general term applied to rubber and plastic sheeting whether fabric reinforced or not. It is usually furnished in rolls.

ROOT ZONE: The part of the soil that is penetrated or can be penetrated by plant roots.

RUBBER: A polymeric material which, at room temperature, is capable of recovering substantially in shape and size after removal of a deforming force. Refers to both synthetic and natural rubber. Also called an elastomer.

RUNOFF: That portion of precipitation or irrigation water that drains from an area as surface flow.

SALINE SOIL: A nonsodic soil containing sufficient soluble salts to impair its productivity but not containing excessive exchangeable sodium.

SAND: Unconsolidated granular mineral material of a certain size range. Particles of rock that will pass the No. 4 United States standard sieve and be retained on the No. 200 sieve. See Figure 3-3.

SANITARY LANDFILL (LAND FILLING): A site where solid waste is disposed of on land in a manner designed to protect the environment by spreading the waste in thin layers, compacting it to the smallest practical volume, and then covering it with soil by the end of the working day.

SCARIFY: To break up and loosen a surface.

SCRIM: A woven, open-mesh reinforcing fabric made from continuous-filament yarn. Used in the reinforcement of polymeric sheeting.

SEAM STRENGTH: Strength of a seam of liner material measured either in shear or peel modes. Strength of the seams is reported either in absolute units, e.g. pounds per inch of width, or as a percent of the strength of the sheeting.

SEED: The fertilized and ripened ovule of a seed plant that is capable, under suitable conditions, of independently developing into a plant similar to the one that produced it. Types of seed include:

Breeder seed: Seed or vegetative propagating material directly controlled by the originating, or in some cases the sponsoring plant breeder, institution, or firm, and which supplies the initial and recurring increase of foundation seed.

Certified seed: The progeny of foundation or registered seed that is so handled as to maintain satisfactory genetic identity and purity and that has been approved and certified by the certifying agency.

Commercial seed: A term used to designate other than recognized varieties of seed in commercial channels.

Common seed: Noncertified seed. It may be a named variety, but not grown under the certification program.

Dormant seed: An internal condition of the chemistry or stage of development of a viable seed that prevents its germination, although good growing temperatures and moisture are provided.

Firm seed: Dormant seeds, other than hard seeds, that neither germinate nor decay during the prescribed test period under the prescribed conditions. Firm ungerminated seeds may be alive or dead.

Foundation seed: Seed stocks that are so handled as to most nearly maintain specific genetic identity and purity. Production must be carefully supervised by the certifying agency and/or the agricultural experiment station.

Hard seed: A physiological condition of seed in which some seeds do not absorb water or oxygen and germinate when a favorable environment is provided.

Registered seed: The program of foundation seed that is so handled as to maintain satisfactory genetic identity and purity and that has been approved and certified by the certifying agency. This class of seed should be of a quality suitable for production of certified seed.

SEED PURITY: The percentage of the desired species in relation to the total quantity of other species, weed seed, and foreign matter.

SEEDBED: The soil prepared by natural or artificial means to promote the germination of seed and the growth of seedlings.

SEEPAGE: Slow movement of water through soil.

SENSITIVITY: The effect of remolding on the consistency of a cohesive soil

SHAKING TEST: A test used to indicate the presence of significant amounts of rock flour, silt, or very fine sand in a fine-grained soil. It consists of shaking a pat of wet soil, having a consistency of thick paste, in the palm of the hand; observing the surface for a glossy or livery appearance; then squeezing the pat; and observing if a rapid apparent drying and subsequent cracking of the soil occurs.

SHEETING: A form of plastic or rubber in which the thickness is very small in proportion to length and width and in which the polymer compound is present as a continuous phase throughout, with or without fabric.

SHRINKAGE LIMIT: The maximum water content at which a reduction in water content will not cause a decrease in volume of the soil mass.

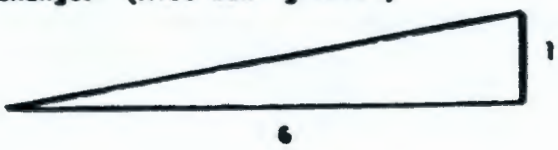
SHRUB: A woody perennial plant differing from a tree by its low stature and by generally producing several basal shoots instead of a single bole.

SILT (INORGANIC SILT) (ROCK FLOUR): Material passing the No. 200 United States standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air-dried.

SILT SIZE: That portion of the soil finer than 0.02 mm. and coarser than 0.002 mm. (0.05 mm. and 0.005 mm. in some cases). See Figure 3-3.

SLAKING: The process of breaking up or sloughing when an indurated soil is immersed in water.

SLOPE: Deviation of a surface from the horizontal expressed as a percentage, by a ratio, or in degrees. In engineering, usually expressed as a ratio of horizontal:vertical change. (Also see "grade.")



Slope = 6:1
(16.7%) (9.5°)

SLOW TEST: See "Consolidated-Drained Test."

SMECTITE: See "Montmorillonite."

SOD: A closely knit ground-cover growth, primarily of grasses.

SODIC SOIL: 1. A soil that contains sufficient sodium to interfere with the growth of most crop plants. 2. A soil in which the exchangeable-sodium percentage is 15 or more. Sodic soils, because of dispersion of the organic matter, have been called black alkali soils; sometimes also called nonsaline-alkali soils.

SOFTENING POINT: Temperature at which a bitumen softens in the ring-and-ball method described in ASTM D2398. Used in the classification of bitumen, particularly of bitumen intending for roofing, because it is indicative of the tendency of a material to flow at elevated temperatures encountered in service.

SOIL: In engineering, sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter.

SOIL ASPHALT: A compacted mixture of soil and asphalt cement. Cutback or emulsified asphalts are usually avoided.

SOIL CEMENT: A tightly compacted mixture of pulverized soil, portland cement and water that, as the cement hydrates, forms a hard, durable, low-strength concrete-like material.

SOIL HORIZON: See "horizon."

SOIL MECHANICS: The application of the laws and principles of mechanics and hydraulics to engineering problems dealing with the behavior and nature of soil as an engineering material.

SOIL ORGANIC MATTER: The organic fraction of the soil that includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. Commonly determined as the amount of organic material contained in a soil sample passed through a 2-millimeter sieve.

SOIL PROFILE (PROFILE): Vertical section of a soil, showing the nature and sequence of the various layers, as developed by deposition or weathering, or both.

SOIL SCIENCE: The study of soil as a natural material; also termed pedology.

SOIL SOLUTION: The aqueous liquid phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble materials.

SOIL STABILIZATION: Chemical or mechanical treatment designed to increase or maintain the stability of a mass of soil or otherwise to improve its engineering properties.

SOIL STERILANT: Biocide applied to soils to prevent plant growth and insect or disease infestation.

SOIL STRUCTURE: In soil mechanics, the arrangement and state of aggregation of soil particles in a soil mass.

FLOCCULENT STRUCTURE: An arrangement composed of flocs of soil particles instead of individual soil particles.

SINGLE-GRAINED STRUCTURE: An arrangement composed of individual soil particles; characteristic structure of coarse-grained soils.

SOIL SUCTION: Tension ("negative pressure") existing in soil water under unsaturated conditions. A complex effect whose causes include capillarity, adsorption, osmosis, etc.

SOLUM: Genetic soil developed by soil-building forces; includes A and B soil horizons, or upper part of soil profile above parent material.

SOLUTION: A homogeneous mixture consisting of a single phase.

SPECIFIC RETENTION: Ratio of (1) the volume of water which a rock or soil, after being saturated, will retain against the pull of gravity to (2) the volume of the rock or soil.

SPECIFIC SURFACE: The ratio of the total surface area of a (finely divided) substance to its volume; or, the surface area of a (finely divided) substance per unit mass.

SPRAY BAR: A long hollow tube with nozzles of any of a number of forms, used to apply a thin layer or coat of a substance in liquid form. Spray bars are attached by hoses and pneumatic lines to pumps to convey the liquid from the storage truck or tank to the nozzles.

SPRIGGING: The planting of a portion of the stem and root of grass.

STATIC HEAD: The sum of Elevation Head and Pressure Head, q.q.v. See also "Head."

STOLON: A horizontal stem which grows along the surface of the soil and roots at the nodes.

STRAIN: The change in length per unit of length in a given direction.

STRESS: Intensity of force. The force per unit area acting within a mass. A vector quantity. Cf. "pressure."

EFFECTIVE STRESS (EFFECTIVE PRESSURE) (INTERGRANULAR PRESSURE): The average normal force per unit area transmitted from grain to grain of a soil mass. It is the stress that is effective in mobilizing internal friction.

NEUTRAL STRESS (PORE PRESSURE) (PORE WATER PRESSURE): Stress transmitted through the pore water (water filling the voids of the soil).

NORMAL STRESS: The stress component normal to a given plane.

SHEAR STRESS (SHEARING STRESS) (TANGENTIAL STRESS): The stress component tangential to a given plane.

STRIKETHROUGH: A term used in the manufacture of fabric-reinforced polymeric sheeting to indicate that two layers of polymer have made bonding contact through the scrim.

STRUCTURE: See "soil structure."

STUBBLE: The basal portion of plants remaining after the top portion has been harvested; also, the portion of the plants, principally grasses, remaining after grazing is completed.

SUBBASE: A layer used in a pavement system between the subgrade and base course, or between the subgrade and portland-concrete pavement.

SUBGRADE: The soil prepared and compacted to support a structure or a pavement system.

SUBSIDENCE: Settling or sinking of the land surface due to any of several factors, such as decomposition of organic material, consolidation, drainage, and underground failure.

SUBSOIL: The B horizons of soils with distinct profiles. In soils with weak profile development, the subsoil can be defined as the soil below the plowed soil (or its equivalent of surface soil), in which roots normally grow. Although a common term, it cannot be defined accurately. It has been carried over from early days when "soil" was conceived only as the plowed soil and that under it as the "subsoil."

SUMP: A pit or well at the lowest point of a circulating or drainage system, in which liquids collect.

SUPPLEMENTAL IRRIGATION: Irrigation to insure or increase crop production in areas where rainfall normally supplies most of the moisture needed.

SURFACE CURE: Curing or vulcanization which occurs in a thin layer on the surface of a manufactured polymeric sheet or other items.

SURFACE IMPOUNDMENT: A natural or artificial basin used to contain liquid wastes. Includes pits, ponds, and lagoons.

SURFACE WATER: All water whose surface is exposed directly to the atmosphere.

SUSPENSION: A two-phase system consisting of a finely divided solid dispersed in a solid, liquid, or gas.

SYMBIOSIS: An arrangement whereby two organisms of different species live in close association, from which one or both may benefit and neither is harmed.

TACKING: The process of binding mulch fibers together by the addition of a sprayed chemical compound.

TALUS: Rock fragments mixed with soil at the foot of a natural slope from which they have been separated.

TAR: Dark, bituminous, viscous liquid obtained by destructive distillation of wood, coal, peat, shale, or other natural materials.

TEAR STRENGTH: The maximum force required to tear a specified specimen, the force acting substantially parallel to the major axis of the test specimen. Measured in both initiated and uninitiated modes. Obtained value is dependent on specimen geometry, rate of extension, and type of fabric reinforcement. Values are reported in stress, e.g. pounds, or stress per unit of thickness, e.g. pounds per inch.

TENSILE STRENGTH: The maximum tensile stress per unit of original cross-sectional area applied during stretching of a specimen to break; units: SI-metric-megapascal or kilopascal; customary - pound per square inch.

TERRACE: An embankment or combination of an embankment and channel constructed across a slope to control erosion by diverting.

THERMOPLASTIC: Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature. Most polymeric liners are supplied in thermoplastic form because the thermoplastic form allows for easier seaming both in the factory and in the field.

THERMOPLASTIC ELASTOMERS: New materials which are being developed, and which are probably related to elasticized polyolefins. Polymers of this type behave similarly to crosslinked rubber. They have a limited upper temperature service range which, however, is substantially above the temperature encountered in waste disposal sites (200°F may be too high for some TPE's).

TILE, DRAIN: Pipe made of burned clay, concrete, or similar material in short lengths, usually laid with open joints to collect and carry excess water from the soil.

TILLAGE: The operation of implements through the soil to prepare seedbeds and root beds.

TOLERANCE: The relative ability of a species to survive a deficiency of an essential growth requirement, such as moisture, light or nutrient supply, or an overabundance of a site factor such as excessive water, toxic salts, etc.

TONNE: Metric ton; one thousand kilograms.

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TOTAL HEAD: See "Head."

TOXICITY: Quality, state, or degree of being toxic or poisonous.

TOXIN: (1) Any of various unstable poisonous compounds produced by some microorganisms and causing certain diseases. (2) Any of various similar poisons, related to proteins, secreted by plants and animals.

TRANSPORTED SOIL: Soil whose particles have been transported and deposited as a sediment.

TREE: A woody perennial plant that reaches a mature height of at least eight feet and has a well-defined stem and a definite crown shape. There is no clear-cut distinction between trees and shrubs. Some plants, such as the willows, may grow as either trees or shrubs.

TRIAXIAL SHEAR TEST (TRIAXIAL COMPRESSION TEST): A test in which a cylindrical specimen of soil encased in an impervious membrane is subjected to a confining pressure and then loaded axially to failure.

TURBULENT FLOW: Flow of fluid in which secondary irregular motions and velocity fluctuations are superimposed on the principal or average flow; in contrast with laminar flow.

ULTIMATE ELONGATION: The elongation of a stretched specimen at the time of break. Usually reported as percent of the original length. Also called elongation at break.

UNCONFINED COMPRESSIVE STRENGTH: See "Compressive Strength."

UNCONSOLIDATED-UNDRAINED TEST (QUICK TEST): A soil test in which the water content of the test specimen remains practically unchanged during the application of the confining pressure and the additional axial (or shear) force.

UNDERCONSOLIDATED SOIL DEPOSIT: A deposit that is not fully consolidated under the existing overburden pressure.

UNDESIRABLE SPECIES: 1. Plant species that are not readily eaten by animals. 2. Species that conflict with or do not contribute to the management objectives.

UNDISTURBED SAMPLE: A soil sample that has been obtained by methods in which every precaution has been taken to minimize disturbance to the sample.

UNIFORMITY COEFFICIENT: See "Coefficient of Uniformity."

UNIT WEIGHT OF WATER: The weight per unit volume of water; nominally equal to 62.4 pounds per cubic foot or 1 gram per cubic centimeter.

UNSATURATED FLOW: The movement of water in a soil which is not filled to capacity with water.

UNSUPPORTED SHEETING: A polymer sheeting one or more plies thick without a reinforcing fabric layer or scrim.

VADOSE: Pertaining to water in the unsaturated zone above the water table.

VANE SHEAR TEST: An inplace shear test in which a rod with thin radial vanes at the end is forced into the soil and the resistance to rotation of the rod is determined.

VAPOR: A gas below its critical point.

VAPOR PRESSURE: Partial pressure of vapor (gaseous phase) of a substance in equilibrium, at a given temperature, with a condensed phase (liquid or solid) of the substance.

VARVED CLAY: Alternating thin layers of silt (or fine sand) and clay formed by variations in sedimentation during the various seasons of the year, often exhibiting contrasting colors when partially dried.

VECTOR: A carrier, e.g., an insect or a rodent, that is capable of transmitting a pathogen from one organism to another.

VELOCITY HEAD: Head possessed by an element of water by virtue of its velocity. Equal to $v2/2g$ where v = velocity, g = acceleration of gravity. Expressed in linear units (e.g. feet). In almost all seepage problems velocity head is very small and is neglected.

VENT: A hole or opening to permit passage or escape, as of a gas.

VISCOSITY GRADE (ASPHALT): Viscosity classification for asphalt cement into ranges specified in ASTM D3381.

VOID: Space in a soil mass not occupied by solid matter. This space may be occupied by air, water, or other gaseous or liquid material.

VOID RATIO: The ratio of (1) the volume of void space to (2) the volume of solid particles in a given soil mass.

VOLUMETRIC SHRINKAGE (VOLUMETRIC CHANGE): The decrease in volume of a soil mass when the water content is reduced from a given percentage to the shrinkage limit; expressed as a percentage of the volume of the soil mass when dried.

VULCANIZATE: A term used to denote the product of the vulcanization of a rubber compound without reference to shape or form.

VULCANIZATION: An irreversible process during which a rubber compound, through a change in its chemical structure, e.g. crosslinking, becomes less plastic and more resistant to swelling by organic liquids, and elastic properties are conferred, improved, or extended over a greater range of temperature.

VULCANIZE: See "Vulcanization."

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WARM-SEASON PLANT: A plant that completes most of its growth during the warm portion of the year, generally late spring and summer.

WATER CONTENT: (Soil Mechanics) The ratio, expressed as a percentage, of (1) the weight of water in a given soil mass to (2) the weight of solid particles. (Soil Science) The amount of water lost from the soil after drying it to constant weight at 105°C, expressed either as the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil.

WATER TABLE: The surface between the zone of saturation and the zone of aeration; that surface of a body of unconfined ground water at which the pressure is equal to that of the atmosphere.

WATER TABLE, PERCHED: See "Perched Water Table."

WATERLOGGED: Saturated with water; soil condition where a high or perched water table is detrimental to plant growth, resulting from over-irrigation, seepage, or inadequate drainage; the replacement of most of the soil air by water.

WEED: An undesired, uncultivated plant.

XEROPHYTE: A plant capable of surviving periods of prolonged moisture deficiency.

ZERO AIR VOIDS CURVE (SATURATION CURVE): The curve showing the zero air voids unit weight as a function of water content.

APPENDIX F

LAWS AND REGULATIONS

The legislative and regulatory authority for remedial actions at uncontrolled hazardous waste sites resides in Public Law 96-510 (the "Superfund Law") and the National Contingency Plan, as published in the Federal Register on July 16, 1982 (Vol 47, No. 137, pp 31180-31243).

For reference purposes, this appendix contains the following extracts from these documents:

- A Table of Contents of P. L. 96-510
- Table of Contents of the NCP
- Text of Subpart F of the NCP, "Hazardous Substance Response"
- Table of Contents of Appendix A to the NCP, "Uncontrolled Hazardous Waste Site Ranking System"

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Public Law 96-510 11 December 1980 96th Congress

"COMPREHENSIVE ENVIRONMENTAL RESPONSE, COMPENSATION, AND LIABILITY ACT OF 1980"

TITLE I - Hazardous Substances Releases, Liability, Compensation

Sec. 101. Definitions
Sec. 102. Reportable Quantities and Additional Designations
Sec. 103. Notices, Penalties
Sec. 104. Response Authorities
Sec. 105. National Contingency Plan
Sec. 106. Abatement Action
Sec. 107. Liability
Sec. 108. Financial Responsibility
Sec. 109. Penalty
Sec. 110. Employee Protection
Sec. 111. Uses of Fund
Sec. 112. Claims Procedure
Sec. 113. Litigation, Jurisdiction, and Venue
Sec. 114. Relationship to Other Law
Sec. 115. Authority to Delegate, Issue Regulations

TITLE II - Hazardous Substance Response Revenue Act of 1980

Sec. 201. Short Title; Amendment of 1954 Code
Subtitle A - Imposition of Taxes on Petroleum and Certain Chemicals
Sec. 211. Imposition of Taxes
Subtitle B - Establishment of Hazardous Substance Response Trust Fund
Sec. 221. Establishment of Hazardous Substance Response Trust Fund
Sec. 222. Liability of United States Limited to Amount in Trust Fund
Sec. 223. Administrative Provisions
Subtitle C - Post-Closure Tax and Trust Fund
Sec. 231. Imposition of Tax
Sec. 232. Post-Closure Liability Trust Fund

TITLE III - Miscellaneous Provisions

Sec. 301. Reports and Studies
Sec. 302. Effective Dates, Savings Provision
Sec. 303. Expiration, Sunset Provision
Sec. 304. Conforming Amendments
Sec. 305. Legislative Veto
Sec. 306. Transportation
Sec. 307. Assistant Administrator for Solid Waste
Sec. 308. Separability

Part 1510, Title 40 of the Code of Federal Regulations is redesignated as Part 300 in a new Subchapter J of chapter I and revised to read as follows:

PART 300—NATIONAL OIL AND HAZARDOUS SUBSTANCES POLLUTION CONTINGENCY PLAN

Subchapter J—Superfund Programs

Subpart A—Introduction

Sec.
300.1 Purpose and objectives.
300.2 Authority.
300.3 Scope.
300.4 Application.
300.5 Abbreviations.
300.6 Definitions.

Subpart B—Responsibility

300.21 Duties of President delegated to Federal agencies.
300.22 Coordination among and by Federal agencies.
300.23 Other assistance by Federal agencies.
300.24 State and local participation.
300.25 Non-government participation.

Subpart C—Organization

300.31 Organizational concepts.
300.32 Planning and coordination.
300.33 Response operations.
300.34 Special forces and teams.
300.35 Multi-regional responses.
300.36 Communications.
300.37 Response equipment.

Subpart D—Plans

300.41 Regional and local plans.
300.42 Regional contingency plans.
300.43 Local contingency plans.

Subpart E—Operational Response Phases for Oil Removal

300.51 Phase I—Discovery and notification.
300.52 Phase II—Preliminary assessment and initiation of action.
300.53 Phase III—Containment, countermeasures, clean-up and disposal.
300.54 Phase IV—Documentation and cost recovery.
300.55 General pattern of response.
300.56 Pollution reports.
300.57 Special considerations.
300.58 Funding.

Subpart F—Hazardous Substance Response

300.61 General.
300.62 State role.
300.63 Phase I—Discovery and notification.
300.64 Phase II—Preliminary assessment.
300.65 Phase III—Immediate removal.
300.66 Phase IV—Evaluation and determination of appropriate response—planned removal and remedial action.
300.67 Phase V—Planned removal.
300.68 Phase VI—Remedial action.
300.69 Phase VII—Documentation and cost recovery.
300.70 Methods of remedying releases.
300.71 Worker health and safety.

Subpart G—Trustees for Natural Resources

300.72 Designation of Federal trustees.
300.73 State trustees.
300.74 Responsibilities of trustees.

Subpart H—Use of Dispersants and Other Chemicals

300.81 General.
Appendix A—Uncontrolled Hazardous Waste Site Ranking System: a users manual.

Authority: Sec. 105, Pub. L. 96-510, 94 Stat. 2794, 42 U.S.C. 9605 and sec. 311(c)(2), Pub. L. 92-500, as amended; 86 Stat. 885, 33 U.S.C. 1321(c)(2); Executive Order 12316, 47 FR 42237 (August 20, 1981); Executive Order 11735, 38 FR 21243 (August 1973).

Subpart F—Hazardous Substance Response

§ 300.61 General.

(a) This subpart establishes methods and criteria for determining the appropriate extent of response authorized by CERCLA when any hazardous substance is released or there is a substantial threat of such a release into the environment, or there is a release or substantial threat of a release into the environment of any pollutant or contaminant which may present an imminent and substantial danger to the public health or welfare.

(b) Section 104(a)(1) of CERCLA authorizes removal or remedial action unless it is determined that such removal or remedial action will be done properly by the owner or operator of the vessel or facility from which the release or threat of release emanates, or by any other responsible party.

(c) In determining the need for and in planning or undertaking Fund-financed action, response personnel should, to the extent practicable, consider the following:

(1) Encourage State participation in response actions (see § 300.63).

(2) Conserve Fund monies by encouraging private party clean-up.

(3) Be sensitive to local community concerns (in accordance with applicable guidance).

(4) Rely on established technology when feasible and cost-effective.

(5) Encourage the participation and sharing of technology by industry and other experts.

§ 300.62 State role.

(a) States are encouraged to undertake actions authorized under this subpart. Section 104(d)(1) of CERCLA authorizes EPA to enter into contracts or cooperative agreements with the State to take response actions authorized under CERCLA, when EPA determines that the State has the capability to undertake such actions.

(b) EPA will provide assistance from the Fund to States pursuant to a contract or cooperative agreement. The agreement can authorize States to undertake most actions specified in this Subpart.

(c)(1) Pursuant to section 104(c)(3) of CERCLA, before any Fund-financed remedial action may be taken, the affected State(s) must enter into a contract or cooperative agreement with the Federal government.

(2) Included in such contract or cooperative agreement must be assurances by the State consistent with requirements of section 104(c)(3) of CERCLA.

(d) Prior to remedial design activity, the State must make a firm commitment, through either a cooperative agreement or a new or amended State contract, to provide funding for remedial implementation by:

(1) Authorizing the reduction of a State credit to cover its share of costs;

(2) Identifying currently available funds earmarked for remedial implementation; or

(3) Submitting a plan with milestones for obtaining necessary funds.

(e) State credits allowed under section 104(c)(3) of CERCLA must be documented on a site-specific basis for State out-of pocket, non-Federal eligible response costs between January 1, 1978, and December 11, 1980. Prior to remedial investigation activity at a site, the State must submit its estimate of these costs as a part of the pre-application package when a cooperative agreement is used, or as a part of the State contract. State credits will be applied against State cost shares for Federally-funded remedial actions. A State cannot be reimbursed from the Fund for credit in excess of its matching share.

(f) Pursuant to section 104(c)(2) of CERCLA, prior to determining any appropriate remedial action, EPA shall consult with the affected State or States.

§ 300.63 Phase I—Discovery or notification.

(a) A release may be discovered through:

(1) Notification in accordance with sections 103(a) or (c) of CERCLA;

(2) Investigation by government authorities conducted in accordance with section 104(e) of CERCLA or other statutory authority;

(3) Notification of a release by a Federal or State permit holder when required by its permit;

(4) Inventory efforts or random or incidental observation by government agencies or the public;

(5) Other sources.

(b) If not reported previously, a release should be promptly reported to the NRC. Section 103(a) of CERCLA requires any person in charge of a vessel or facility to immediately notify the NRC as soon as he has knowledge of a release (other than a federally permitted release) of a hazardous substance from such vessel or facility in an amount equal to or greater than the reportable quantity determined pursuant to section 102(b) of CERCLA. The NRC shall convey the notification expeditiously to appropriate government agencies, and in the case of notices received pursuant to section 103(a), the NRC shall also notify the Governor of any affected State.

(c) Upon receipt of a notification of a release, the NRC shall promptly notify the appropriate OSC.

§ 300.64 Phase II—Preliminary assessment.

(a) A preliminary assessment of a release identified for possible CERCLA response should be undertaken by the lead agency. If the reported release potentially requires immediate removal, the preliminary assessment should be done as promptly as possible. Other releases shall be assessed as soon as practicable. The lead agency should base its assessment on readily available information. This assessment may include:

(1) Evaluation of the magnitude of the hazard;

(2) Identification of the source and nature of the release;

(3) Determination of the existence of a non-Federal party or parties ready, willing, and able to undertake a proper response; and

(4) Evaluation of factors necessary to make the determination of whether immediate removal is necessary.

(b) A preliminary assessment of releases from hazardous waste management facilities may include collection or review of data such as site management practices, information from generators, photographs, analysis of historical photographs, literature searches, and personal interviews conducted as appropriate. In addition perimeter (off-site) inspection may be necessary to determine the potential for a release. Finally, if more information is needed, a site visit may be performed, if conditions are such that it may be performed safely.

(c) A preliminary assessment should be terminated when the OSC determines:

(1) There is no release;

(2) The source is neither a vessel nor a facility;

(3) The release involves neither a hazardous substance, nor a pollutant or contaminant that may pose an imminent and substantial danger to public health or welfare;

(4) The amount released does not warrant Federal response;

(5) A party responsible for the release, or any other person, is providing appropriate response, and on-scene monitoring by the government is not recommended or approved by the lead agency; or

(6) The assessment is completed.

§ 300.65 Phase III—Immediate removal.

(a) In determining the appropriate extent of action to be taken at a given release, the lead agency shall first review the preliminary assessment to determine if immediate removal action is appropriate. Immediate removal action shall be deemed appropriate in those cases in which the lead agency determines that the initiation of immediate removal action will prevent or mitigate immediate and significant risk of harm to human life or health or to the environment from such situations as:

(1) Human, animal, or food chain exposure to acutely toxic substances;

(2) Contamination of a drinking water supply;

(3) Fire and/or explosion; or

(4) Similarly acute situations.

(b) If the lead agency determines that immediate removal is appropriate, defensive actions should begin as soon as possible to prevent or mitigate danger to the public health, welfare, or the environment. Actions may include, but are not limited to:

(1) Collecting and analyzing samples to determine the source and dispersion of the hazardous substance and documenting those samples for possible evidentiary use.

(2) Providing alternative water supplies.

(3) Installing security fencing or other measures to limit access.

(4) Controlling the source of release.

(5) Measuring and sampling.

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(6) Moving hazardous substances off-site for storage, destruction, treatment, or disposal provided that the substances are moved to a facility that is in compliance with subtitle C of the Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act.

(7) Placing physical barriers to deter the spread of the release.

(8) Controlling the water discharge from an upstream impoundment.

(9) Recommending to appropriate authorities the evacuation of threatened individuals.

(10 Using chemicals and other materials in accordance with Subpart H to restrain the spread of the substance and to mitigate its effects.

(11) Executing damage control or salvage operations.

(c) Immediate removal actions are complete when, in the opinion of the lead agency, the criteria in subsection (a) of § 300.65 are no longer met and any contaminated waste materials transported off-site have been treated or disposed of properly.

(d) Immediate removal action shall be terminated after $1 million has been obligated for the action or six months have elapsed from the date of initial response to a release or threatened release unless it is determined that:

(1) Continued response actions are immediately required to prevent, limit or mitigate an emergency;

(2) There is an immediate risk to public health or welfare or the environment; and

(3) Such assistance will not otherwise be provided on a timely basis.

(e) If the lead agency determines that the release still may require planned removal or remedial action, the lead agency or a State may initiate, either simultaneously or sequentially, Phase IV or V as appropriate.

§ 300.66 Phase IV—Evaluation and determination of appropriate response—planned removal and remedial action.

(a) The purpose of this phase is to determine the appropriate action when the preliminary assessment indicates that further response may be necessary or when the OSC requests and the lead agency concurs that further response should follow an immediate removal action.

(b) As soon as practicable, an inspection will be undertaken to assess the nature and extent of the release and to assist in determining its priority for Fund-financed response.

(c)(1) Pursuant to section 104 (b) and (e) of CERCLA, the responsible official may undertake investigations, monitoring, surveys, testing and other information gathering as appropriate. These efforts shall be undertaken jointly by the Federal or State officials responsible for providing Fund-financed response and those responsible for enforcing legal requirements.

(2) A major objective of an inspection is to determine if there is any immediate danger to persons living or working near the facility. In general, the collection of samples should be minimized during inspection activities; however, situations in which there is an apparent risk to the public should be treated as exceptions to that practice. Examples of apparent risk include use of nearby wells for drinking water, citizen complaints of unusual taste or odor in drinking water, or chemical odors or unusual health problems in the vicinity of the release. Under those circumstances, a sampling protocol should be developed for the inspection to allow for the earliest possible detection of any human exposure to hazardous substances. The site inspection may also address:

(i) Determining the need for immediate removal action;

(ii) Assessing amounts, types and location of hazardous substances stored;

(iii) Assessing potential for substances to migrate from areas where they were originally located;

(iv) Determining or documenting immediate threats to the public or environment.

(d) *Methods for Establishing Priorities.* (1) States that wish to submit candidates for the National Priorities List must use the Hazard Ranking System (included in Appendix A) to rank the releases.

(2) EPA will notify States at least thirty days prior to the deadline for submitting candidate releases for the National Priorities List or any subsequent revisions.

(3) Each State may designate a facility as the State's highest priority release by certifying, in writing signed by the Governor or the Governor's designee, that the facility presents the greatest danger to public health, welfare or the environment among known facilities in the State.

(e) *National Priorities List.* (1) Compiling the National Priorities List—EPA Regional Office will review State hazard rankings to ensure uniform application of the Hazard Ranking System and may add, in consultation with the States, any additional priority releases known to EPA. The States' priorities will be reviewed and consolidated by EPA Headquarters into a National Priorities List pursuant to section 105(8) of CERCLA. To the extent practicable, each State's designated top priority facility will be included among the one hundred highest priority facilities.

(2) No facilities presently owned by the Federal Government will be included on the National Priorities List.

(3) EPA will submit the recommended National Priorities List to the NXT for review and comment.

(4) EPA will publish a proposed National Priorities List for public comment.

(5) The National Priorities List is presented in Appendix B.

(6) Ranking of Releases—Similar hazard ranking scores assigned to releases cannot accurately differentiate among risks represented by the releases. Thus, in order to avoid misleading the public that real differences in risk exist, similar scores may be grouped on the National Priorities List.

(7) EPA will revise and publish the National Priorities List at least once annually. In addition, revisions will give notice of the deletion (if any) of releases previously listed.

§ 300.67 Phase V—Planned removal.

(a) Planned removal may be undertaken pursuant to a contract or cooperative agreement when the lead agency determines that:

(1) There would be a substantial cost savings by continuing a response action with the equipment and resources mobilized for an immediate removal action taken pursuant to § 300.64, but terminate pursuant to § 300.64(c); or

(2) The public and/or environment will be at risk from exposure to hazardous substances if response is delayed at a release not on the National Priorities List.

(b) Planned removal must be requested by the Governor of the affected State or his designee. Requests must include:

(1) A description of the nature and extent of the release;

(2) A description of actions taken or underway at the site;

(3) A description of the proposed planned removal; and

(4) Assurances that the State will pay at least 10 percent of the costs of the action, including all future maintenance or at least 50 percent or such greater amount as EPA may determine appropriate, taking into account the degree of responsibility of the State or political subdivision, of any sums expended in response to a release at a facility that was owned at the time of any disposal of hazardous substances thereto by the State or a political subdivision thereof.

(c) Among the factors that EPA will use to determine whether a planned removal is appropriate under § 300.67(a)(2) are the following:

(1) Actual or potential direct contact with hazardous substances by nearby population;

(2) Contaminated drinking water at the tap;

(3) Hazardous substances in drums, barrels, tanks, or other bulk storage containers, that are known to pose a serious threat to public health or the environment;

(4) Highly contaminated soils largely at or near surface, posing a serious threat to public health or the environment;

(5) Serious threat of fire or explosion; or

(6) Weather conditions that may cause substances to migrate and pose a serious threat to public health or the environment.

(d) Planned removal actions shall be terminated when the lead agency determines that the risk to the public health or the environment has been abated. In making this determination, the lead agency shall consider whether the factors listed in § 300.68(c) continue to apply to the release and whether any contaminated waste materials transported off-site have been treated or disposed of properly.

(e) Unless the EPA finds that (1) continued response actions are immediately required to prevent, limit or mitigate an emergency, (2) there is an immediate risk to public health or welfare or the environment, and (3) such assistance will not otherwise be provided on a timely basis, obligations from the Fund, other than those authorized by section 104(b) of CERCLA, shall not continue after $1 million has been obligated for response actions or six months has elapsed from the date of initial response to the release.

§ 300.68 Phase VI—Remedial action.

(a) Remedial actions taken pursuant to this section (other than responses at Federal facilities) are those responses to releases on the National Priorities List that are consistent with permanent remedy to prevent or mitigate the migration of a release of hazardous substances into the environment.

(b) States are encouraged to undertake Fund-financed remedial actions in accordance with § 300.62 of this Plan.

(c) As an alternative or in addition to Fund-financed remedial action, the lead agency may seek, through voluntary agreement or administrative or judicial process, to have those persons responsible for the release clean up in a manner that effectively mitigates and minimizes damage to, and provides adequate protection of, public health, welfare, and the environment. The lead agency shall evaluate the adequacy of clean-up proposals submitted by responsible parties or determine the level of clean-up to be sought through enforcement efforts, by consideration of the factors discussed in paragraphs (e) through (j) of this section. The lead agency will not, however, apply the cost balancing considerations discussed in paragraph (k) of this section to determine the appropriate extent of responsible party clean-up.

(d)(1) The lead agency, in cooperation with State(s), will examine available information and determine, based on the factors in paragraph (g) of this section, the type or types of remedial response that may be needed to remedy the release. This scoping will serve as the basis for requesting funding for a remedial investigation and feasibility study.

(i) In the case of initial remedial measures, a single request may be made by a State for funding the remedial investigation, feasibility study, design and implementation, in order that such measures may be expedited while continuing the remainder of the remedial planning process.

(ii) In the case of source control or off-site remedial action, the initial funding request should be for the remedial investigation and feasibility study. Requests for funding of design and implementation should be made after the completion of the feasibility study.

(2) As a remedial investigation progresses, the project may be modified if the lead agency determines that, based on the factors in 300.68(e), such modifications would be appropriate.

(e) In determining the appropriate extent of remedial action, the following factors should be used to determine the type or types of remedial action that may be appropriate:

(1) In some instances, initial remedial measures can and should begin before final selection of an appropriate remedial action if such measures are determined to be feasible and necessary to limit exposure or threat of exposure to a significant health or environmental hazard and if such measures are cost-effective. Compliance with § 300.67(b) is a prerequisite to taking initial remedial measures. The following factors should be used in determining whether initial remedial measures are appropriate:

(i) Actual or potential direct contact with hazardous substances by nearby population. (Measures might include fences and other security precautions.)

(ii) Absence of an effective drainage control system (with an emphasis on run-on control). (Measures might include drainage ditches.)

(iii) Contaminated drinking water at the tap. (Measures might include the temporary provision of an alternative water supply.)

(iv) Hazardous substances in drums, barrels, tanks, or other bulk storage containers, above surface posing a serious threat to public health or the environment. (Measures might include transport of drums off-site.)

(v) Highly contaminated soils largely at or near surface, posing a serious threat to public health or the environment. (Measures might include temporary capping or removal of highly contaminated soils from drainage areas.)

(vi) Serious threat of fire or explosion or other serious threat to public health or the environment. (Measures might include security or drum removal.)

(vii) Weather conditions that may cause substances to migrate and to pose a serious threat to public health or the environment. (Measures might include stabilization of berms, dikes or impoundments.)

(2) Source control remedial actions may be appropriate if a substantial concentration of hazardous substances remain at or near the area where they were originally located and inadequate barriers exist to retard migration of substances into the environment. Source control remedial actions may not be appropriate if most substances have migrated from the area where originally located or if the lead agency determines that the substances are adequately contained. Source control remedial actions may include alternatives to contain the hazardous substances where they are located or eliminate potential contamination by transporting the hazardous substances to a new location. The following criteria should be assessed in determining whether and what type of source control remedial actions should be considered:

(i) The extent to which substances pose a danger to public health, welfare, or the environment. Factors which should be considered in assessing this danger include:

(A) Population at risk;

(B) Amount and form of the substance present;

(C) Hazardous properties of the substances;

(D) Hydrogeological factors (e.g. soil permeability depth to saturated zone, hydrologic gradients, proximity to a drinking water aquifer); and

(E) Climate (rainfall, etc.).

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(ii) The extent to which substances have migrated or are contained by either natural or man-made barriers.

(iii) The experiences and approaches used in similar situations by State and Federal agencies and private parties.

(iv) Environmental effects and welfare concerns.

(3) In some situations it may be appropriate to take action (referred to as offsite remedial actions) to minimize and mitigate the migration of hazardous substances and the effects of such migration. These actions may be taken when the lead agency determines that source control remedial actions may not effectively mitigate and minimize the threat and there is a significant threat to public health, welfare, or the environment. These situations typically will result from contamination that has migrated beyond the area where the hazardous substances were originally located. Offsite measures may include provision of permanent alternative water supplies, management of a drinking water aquifer plume or treatment of drinking water aquifers. The following criteria should be used in determining whether and what type of offsite remedial actions should be considered:

(i) Contribution of the contamination to an air, land or water pollution problem.

(ii) The extent to which the substances have migrated or are expected to migrate from the area of their original location and whether continued migration may pose a danger to public health, welfare or environment.

(iii) The extent to which natural or man-made barriers currently contain the hazardous substances and the adequacy of the barriers.

(iv) The factors listed in paragraph (e)(2)(i) of this section.

(v) The experiences and approaches used in similar situations by State and Federal agencies and private parties.

(iv) Environmental effects and welfare concerns.

(f) A remedial investigation should be undertaken by the lead agency (or responsible party if the responsible party will be developing a clean-up proposal) to determine the nature and extent of the problem presented by the release. This includes sampling and monitoring, as necessary, and includes the gathering of sufficient information to determine the necessity for and proposed extent of remedial action. During the remedial investigation, the original scoping of the project may be modified based on the factors in § 300.68(e). Part of the remedial investigation involves assessing whether the threat can be mitigated and minimized by controlling the source of the contamination at or near the area where the hazardous substances were originally located (source control remedial actions) or whether additional actions will be necessary because the hazardous substances have migrated from the area of their original location (offsite remedial actions).

(g) *Development of Alternatives.* A limited number of alternatives should be developed for either source control or offsite remedial actions (or both) depending upon the type of response that has been identified under paragraphs (e) and (f) of this section as being appropriate. One alternative may be a no-action alternative. No-action alternatives are appropriate, for example, when response action may cause a greater environmental or health danger than no action. These alternatives should be developed based upon the assessment conducted under paragraphs (e) and (f) of this section and reflect the types of source control or offsite remedial actions determined to be appropriate under paragraphs (e) and (f) of this section.

(h) *Initial Screening of Alternatives.* The alternatives developed under paragraph (g) of this section will be subjected to an initial screening to narrow the list of potential remedial actions for further detailed analysis. Three broad criteria should be used in the initial screening of alternatives:

(1) *Cost.* For each alternative, the cost of installing or implementing the remedial action must be considered, including operation and maintenance costs. An alternative that far exceeds (e.g. by an order of magnitude) the costs of other alternatives evaluated and that does not provide substantially greater public health or environmental benefit should usually be excluded from further consideration.

(2) *Effects of the Alternative.* The effects of each alternative should be evaluated in two ways: (i) Whether the alternative itself or its implementation has any adverse environmental effects; and (ii) for source control remedial actions, whether the alternative is likely to achieve adequate control of source material, or for offsite remedial actions, whether the alternative is likely to effectively mitigate and minimize the threat of harm to public health, welfare or the environment. If an alternative has significant adverse effects, it should be excluded from further consideration. Only those alternatives that effectively contribute to protection of public health, welfare, or the environment should be considered further.

(3) *Acceptable Engineering Practices.* Alternatives must be feasible for the location and conditions of the release, applicable to the problem, and represent a reliable means of addressing the problem.

(i) *Detailed Analysis of Alternatives.*

(1) A more detailed evaluation will be conducted of the limited number of alternatives that remain after the initial screening in paragraph (h).

(2) The detailed analysis of each alternative should include:

(A) Refinement and specification of alternatives in detail, with emphasis on use of established technology;

(B) Detailed cost estimation, including distribution of costs over time;

(C) Evaluation in terms of engineering implementation, or constructability;

(D) An assessment of each alternative in terms of the extent to which it is expected to effectively mitigate and minimize damage to, and provide adequate protection of, public health, welfare, and the environment, relative to the other alternatives analyzed; and

(E) An analysis of any adverse environmental impacts, methods for mitigating these impacts, and costs of mitigation.

(3) In performing the detailed analysis of alternatives, it may be necessary to gather additional data in order to complete the analysis.

(j) The appropriate extent of remedy shall be determined by the lead agency's selection of the remedial alternative which the agency determines is cost-effective (i.e. the lowest cost alternative that is technologically feasible and reliable and which effectively mitigates and minimizes damage to and provides adequate protection of public health, welfare, or the environment).

(k) Section 104(c)(4) of CERCLA requires that the need for protection of public health, welfare and the environment at the facility under consideration be balanced against the amount of money available in the Fund to respond to other sites which present or may present a threat to public health or welfare or the environment, taking into consideration the need for immediate action. Accordingly, in determining the appropriate extent of remedy for Fund-financed response, the lead agency also must consider the need to respond to other releases with Fund monies.

§ 300.69 Phase VII—Documentation and cost recovery.

(a) During all phases, documentation shall be collected and maintained to support all actions taken under this Plan, and to form the basis for cost recovery. In general, documentation should be sufficient to provide the

source and circumstances of the condition, the identity of responsible parties, accurate accounting of Federal costs incurred, and impacts and potential impacts to the public health, welfare and environment.

(b) The information and reports obtained by the lead agency for Fund-financed response action should be transmitted to the RRC. Copies can then be forwarded to the NRT, members of the RRT, and others as appropriate.

§ 300.70 Methods of remedying releases.

(a) The following section lists methods for remedying releases that may be considered by the lead agency in taking response action. This list of methods should not be considered inclusive of all possible methods of remedying releases.

(b) *Engineering Methods for On-Site Actions.*—(1)(i) *Air emissions control*—The control of volatile gaseous compounds should address both lateral movement and atmospheric emissions. Before gas migration controls can be properly installed, field measurements to determine gas concentrations, pressures, and soil permeabilities should be used to establish optimum design for control. In addition, the types of hazardous substances present, the depth to which they extend, the nature of the gas and the subsurface geology of the release area should, if possible, be determined. Typical emission control techniques include the following:

(A) Pipe vents;

(B) Trench vents;

(C) Gas barriers;

(D) Gas collection systems;

(E) Overpacking.

(ii) *Surface water controls*—These are remedial techniques designed to reduce waste infiltration and to control runoff at release areas. They also serve to reduce erosion and to stabilize the surface of covered sites. These types of control technologies are usually implemented in conjunction with other types of controls such as the elimination of ground water infiltration and/or waste stabilization, etc. Technologies applicable to surface water control include the following:

(A) Surface seals;

(B) Surface water diversion and collection systems:

(1) Dikes and berms;

(2) Ditches, diversions, waterways;

(3) Chutes and downpipes;

(4) Levees;

(5) Seepage basins and ditches;

(6) Sedimentation basins and ponds;

(7) Terraces and benches.

(C) Grading;

(D) Revegetation.

(iii) *Ground water controls*—Ground water pollution is a particularly serious problem because, once an aquifer has been contaminated, the resource cannot usually be cleaned without the expenditure of great time, effort and resources. Techniques that can be applied to the problem with varying degrees of success are as follows:

(A) Impermeable barriers:

(1) Slurry walls;

(2) Grout curtains;

(3) Sheet pilings.

(B) Permeable treatment beds;

(C) Ground water pumping;

(1) Water table adjustment;

(2) Plume containment.

(D) Leachate control—Leachate control systems are applicable to control of surface seeps and seepage of leachate to ground water. Leachate collection systems consist of a series of drains which intercept the leachate and channel it to a sump, wetwell, treatment system, or appropriate surface discharge point. Technologies applicable to leachate control include the following:

(1) Subsurface drains;

(2) Drainage ditches;

(3) Liners.

(iv) *Contaminated water and sewer lines*—Sanitary sewers and municipal water mains located down gradient from hazardous waste disposal sites may become contaminated by infiltration of leachate or polluted ground water through cracks, ruptures, or poorly sealed joints in piping. Technologies applicable to the control of such contamination to water and sewer lines include:

(A) Grouting;

(B) Pipe relining and slowing;

(C) Sewer relocation.

(2) *Treatment technologies.* (i) *Gaseous emissions treatment*—Gases from waste disposal sites frequently contain malodorous and toxic substances, and thus require treatment before release to the atmosphere. There are two basic types of gas treatment systems:

(A) Vapor phase adsorption;

(B) Thermal oxidation.

(ii) *Direct waste treatment methods*—In most cases, these techniques can be considered long-term permanent solutions. Many of these direct treatment methods are not fully developed and the applications and process reliability are not well demonstrated. Use of these techniques for waste treatment may require considerable pilot plant work. Technologies applicable to the direct treatment of wastes are:

(A) Biological methods:

(1) Treatment via modified conventional wastewater treatment techniques;

(2) Anaerobic, aerated and facultative lagoons;

(3) Supported growth biological reactors.

(B) Chemical methods:

(1) Chlorination;

(2) Precipitation, flocculation, sedimentation;

(3) Neutralization;

(4) Equalization;

(5) Chemical oxidation.

(C) Physical methods:

(1) Air stripping;

(2) Carbon absorption;

(3) Ion exchange;

(4) Reverse osmosis;

(5) Permeable bed treatment;

(6) Wet air oxidation;

(7) Incineration.

(iii) *Contaminated soils and sediments*—In some cases where it can be shown to be cost-effective, contaminated sediments and soils will be treated on the site. Technologies available include:

(A) Incineration;

(B) Wet air oxidation;

(C) Solidification;

(D) Encapsulation;

(E) In situ treatment;

(1) Solution mining, (soil washing or soil flushing);

(2) Neutralization/detoxification;

(3) Microbiological degradation.

(c) *Offsite Transport for Storage, Treatment, Destruction or Secure Disposition.*—(1) *General*—Offsite transport or storage, treatment, destruction, or secure disposition offsite may be provided in cases where EPA determines that such actions:

(i) Are more cost-effective than other forms of remedial actions;

(ii) Will create new capacity to manage, in compliance with Subtitle C of the Solid Waste Disposal Act, hazardous substances in addition to those located at the affected facility; or

(iii) Are necessary to protect public health, welfare, or the environment from a present or potential risk which may be created by further exposure to the continued presence of such substances or materials.

(2) *Contaminated soils and sediments may be removed from the site.* Technologies used to remove contaminated sediments on soils include:

(i) Excavation;

(ii) Hydraulic dredging;

(iii) Mechanical dredging.

(d) *Provision of Alternative Water Supplies*—Alternative water supplies can be provided in several ways:

(1) Provision of individual treatment units;

(2) Provision of water distribution systems;

(3) Provision of new wells in a new location or deeper wells;

(4) Provision of cisterns;

(5) Provision of bottled or treated water;

(6) Provision of upgraded treatment for existing distribution systems.

(c) *Relocation*—Permanent relocation of residents, businesses, and community facilities may be provided where it is determined that human health is in danger and that, alone or in combination with other measures, relocation would be cost-effective and environmentally preferable to other remedial response. Temporary relocation may also be taken in appropriate circumstances.

§ 300.71 Worker health and safety.

Lead agency personnel should be aware of hazards, due to a release of hazardous substances, to human health and safety and exercise great caution in allowing civilian or government personnel into an affected area until the nature of the release has been ascertained. Accordingly, the OSC or responsible official must conform to applicable OSHA requirements and other guidance. All private contractors who are working at the scene of a release must conform to applicable provisions of the Occupational Safety and Health Act and any other requirements deemed necessary by the lead agency.

Appendix A—Uncontrolled Hazardous Waste Site Ranking System: A User's Manual

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APPENDIX G

QUALITY-CONTROL TEST METHODS

The following test methods are described in this Appendix.

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Method	Number
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Water Content/Density/Compactive Effort	
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* Generally recommended or preferred method.

These descriptions are brief and are presented primarily for information purposes. Wherever a reference is given, that reference should be consulted for directors as to the actual conduct of the test. Test data sheets are included as illustrative examples with many of the test methods given. All of these sample data sheets came from actual construction sites where they were in use. They should not be regarded as specifically recommended forms, however, as they contain some inconsistencies and omissions of desirable data. They are included for purposes of illustration only.

Parameter Measured: Water Content

Title of Test Method: Standard Oven-Dry

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried in an oven.

Test Method

(1) Apparatus: Drying oven (thermostatically controlled, preferably of the force-draft type), balance sensitive to 0.01 g., specimen containers (tares) with lids, and a desiccator.

(2) Procedure: The procedure for this method consists simply of taking a specimen of known weight, placing it into an oven and drying it at a particular temperature and specified time. Upon drying the specimen is removed, reweighed and the moisture content is calculated.

(3) Reference: ASTM D 2216.

Limitations: With many soils, close control of water content during field compaction is necessary to develop a required density, strength and hydraulic conductivity in the soil mass. Oven-drying is the standard test for determining water content of soils in geotechnical engineering practice. However, the method does not lend itself easily to field use. Although temperature controlled ovens are currently available on some construction sites, they require 4 to 12 hours for drying which may be excessive for close control of field compaction. All soils can be tested for moisture content by oven-drying.

Status of the Method: Oven-drying of soil is the accepted laboratory method among the geotechnical engineering profession for determination of water content.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. An example data sheet is provided.

Name: _____ Sample Numbers: _____

Date: _____ Sheet Number: _____

WATER CONTENT DETERMINATIONS
DATA AND COMPUTATION SHEET

NOTE: Tare is weight of container (watch glasses and clip, Petri dishes, can, etc.)

$$\text{Water Content} = w = \frac{\text{Wt. of Water}}{\text{Wt. of Dry Soil}} \cdot 100\%$$

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

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Parameter Measured: Water Content

Title of Test Method: Standard Nuclear Moisture/Density Gage

Principle of Test Method: This method measures in-place water content by directing fast neutrons of known intensity into the soil and measuring the intensity of slow or moderated neutrons reflected back.

Test Method

(1) Apparatus: Fast neutron source, slow neutron detector (readout device and housing) and reference standard and site preparation device.

(2) Procedure: This method allows the determination of water content of soil and soil aggregate in place through the use of nuclear equipment. The equipment is calibrated to determine water content, as weight of water per unit volume of material. Water content as normally used is defined as the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles. It is determined with this procedure by dividing the water content by the dry unit weight of the soil. Therefore, computation of water content using the nuclear equipment also requires the determination of the dry unit weight of the material being tested. Most available nuclear equipment has the provision for measuring both the water content and the wet unit weight. The difference between these two measurements gives the dry unit weight. Recent units give a direct readout of water content and dry unit weight. Some can be set to yield percent compaction.

(3) Reference: ASTM D 3017.

Limitations: The method described is useful as a rapid, nondestructive technique for the in-place determination of the water content of soil. The fundamental assumptions inherent in the method are that the hydrogen present is in the form of water as defined by ASTM D 2216, and that the material under test is homogeneous. Test results may be affected by chemical composition, sample heterogeneity, and, to a lesser degree, material density and the surface texture of the material being tested. The technique also exhibits spatial bias in that the apparatus is more sensitive to certain regions of the material under test. The nuclear method, which is applicable to a wide range of soils, requires operation by an experienced technician in order to obtain reliable measurements. A weakness in the nuclear method is that a sample is not taken to determine the water content, and thus the test results cannot be compared to the other water content methods, e.g. the oven-dry method. In addition, this method requires equipment that utilizes radioactive materials which themselves may be hazardous to the health of the operator. Effective operator instructions together with routine safety procedures are essential to the proper operation of this type of equipment.

Status of the Method: Nuclear gages offer a rapid and accurate means for obtaining water content values for a wide variety of soils. Recent advances

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in the design of nuclear equipment and a better understanding of the nuclear principles involved have led to increasingly widespread use of nuclear gages in earthwork construction control.

Calibration Procedure: The apparatus must be calibrated against a reliable direct method (e.g. oven-drying).

Documentation of Test: Items to be recorded include the water content and the wet unit weight. An example data sheet is provided.

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		DATA SHEET FOR FIELD DENSITY TEST NUCLEAR GAUGE METHOD	
A	Moisture Standard Count	Gauge Type	Serial No
J	Density Standard Count		

FOR	
JOB	JOB NO.
SOURCE OF MATERIAL	DATE

	TEST LOCATION							
	ELEVATION							
	TEST NUMBER							
C	Moisture Count							
D	Moisture Count Ratio	$\frac{C}{A}$						
E	Density Count							
F	Air-Gap Count (if used)							
G	Density Count Ratio	$\frac{E}{B}$ or $\frac{E}{F}$						
H	Density, Wet Wt., PCF	From G & Chart						
I	Moisture Content, PCF	From D & Chart						
J	Density, Dry Wt., PCF	H - I						
K	MOISTURE CONTENT, PERCENT	$\frac{I}{J}$						
L	OPTIMUM MOISTURE, PERCENT	See Curve						
M	DENSITY, DRY WT., PCF	From J						
N	THEORETICAL DENSITY, PCF	See Curve						
O	PERCENT COMPACTION	$\frac{M}{N} \times 100$						
P	REQUIRED PERCENT COMPAC.	See Specs.						
Q	MODE & PROBE DEPTH, IN.							
R	TYPE OF MATERIAL							

Laboratory No.	Technician(s)

Method No. 3

Parameter Measured: Water Content

Title of Test Method: Gas Burner

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried.

Test Method

(1) Apparatus: Gas stove, frying pan, balance and stirring rods.

(2) Procedure: This method covers determination of the approximate moisture content of soils by means of a gas-burner stove, in field control of earthwork. The gas burner method involves the weighing of a moist sample, placing the sample in a pan on the stove and drying to constant weight, with occasional stirring of the sample to prevent burning. The dry sample, permitted to cool, is then reweighed and the moisture content determined.

(3) Reference: N/A

Limitations: The gas-burner method is used extensively for testing gravelly material. Two or more samples may be tested concurrently. When care is exercised to prevent overheating or burning the sample, the testing time is usually about 1/2 hour. The method is inaccurate for organic soils or those containing particles with loosely bound water of hydration, unless the drying is accomplished at a temperature of not more than 140°F (60°C) for 1 hour or longer.

Status of the Method: The gas-burner method is used extensively as a rapid method for testing gravelly soils in field control of earthwork.

Calibration Procedure: Calibrate against Method No. 1.

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

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Method No. 4

Parameter Measured: Water Content

Title of Test Method: Alcohol Burning

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried by alcohol burning.

Test Method

(1) Apparatus: Metal pan, balance, denatured alcohol and stirring rods.

(2) Procedure: This method determines the approximate moisture content of soil by burning alcohol that has been added to the soil. General procedure consists of placing a weighted quantity of moist soil in a pan, adding alcohol and stirring the mixture, then igniting the alcohol. After ignition and complete removal of the moisture by burning, the sample is reweighed and its moisture content calculated.

(3) Reference: N/A

Limitations: The alcohol burning test is a rapid inexpensive method for determining the moisture content of soils. The method is usable with non-cohesive and cohesive material. The method should not be used however if the soil contains a larger proportion of clay, gypsum, calcareous matter or organic matter. A large quantity of alcohol is required for testing coarse gravelly material. For multiple burnings, testing time can take more than 1/2 hour. In terms of safety the alcohol burning test possesses the potential for accidental fire. Care should be exercised not to have alcohol on hand or in an open storage container near the testing apparatus during the ignition phase of the test. The alcohol should be stored in a safety container.

Status of the Method: The alcohol burning method of obtaining the moisture content of soil in the field has given satisfactory results. Its use in the field has been established.

Calibration Procedure: Calibrate against Method No. 1.

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Parameter measured: Water Content

Title of Test Method: Calcium Carbide (Speedy)

Principle of Test Method: This method determines the water content of a soil sample by measuring the pressure developed when measured quantities of the soil sample and powdered calcium carbide are mixed.

Test Method

(1) Apparatus: Calcium carbide pressure moisture tester, tared scale, two each 1-1/4 in. steel balls, brush, cloth and scoop.

(2) Procedure: The calcium carbide gas pressure method for determining water content consists of mixing measured quantities of moist soil and powdered calcium carbide in a closed chamber and measuring the pressure developed by the formation of acetylene gas. The reaction of calcium carbide and water forms acetylene gas and calcium hydroxide. The pressure developed is directly related to the amount of water entering into the reaction.

(3) Reference: AASHTO T 217.

Limitations: Only two sizes of testers are commercially available to test for moisture content using this method: (1) 26 gram capacity model and (2) a six-gram capacity model. The small chamber capacities of these devices control the soil sample size to be used. As a result, this method is unsuitable for representative samples of coarse granular material. AASHTO T 217 recommends that this method should not be used on granular material having particles large enough to affect the accuracy of the test--in general any appreciable amount retained on 4.75 mm sieves. If a six-gram sample is used (according to AASHTO T 217), the sample should not contain any particles that will be retained on the 2.00 mm sieve. The testing of heavy clays with this method requires special handling.

Status of the Method: The apparatus for this method is relatively inexpensive and well adopted to field testing. Use in the United States is extensive. In the field the calcium carbide method has been used extensively in the control of embankment construction. Normal testing time is less than 10 min. A moderate amount of training of operators is required. The calcium carbide method is a standard method for rapid water content determination referenced under AASHTO.

Calibration Procedure: A calibration curve is required.

Documentation of Test: Items to be recorded include soil sample weight, powdered calcium carbide weight and resultant gas pressure. No example data sheet is provided.

Parameter Measured: Water Content

Title of Test Method: Microwave Oven

Principle of Test Method: This method determines the water content of a soil by first weighing it wet and then again after it has been dried in the oven.

Test Method

(1) Apparatus: Microwave oven suitable for drying, balance, specimen containers.

(2) Procedure: The procedure for this method is the same as that for the Standard Oven-Dry method. That is, a specimen is placed wet onto a balance and weighed. It is then placed in a microwave oven and dried completely. It is then weighed again. The weight difference was the water content.

(3) Reference: N/A

Limitations: Microwave ovens are not noted for their drying ability. There are necessary safety precautions when using a microwave oven.

Status of the Method: This method is not commonly used. Although a microwave oven heats much more rapidly than a conventional oven, it is an erratic dryer at best. Thus this method should probably only be used for soils expected to have a relatively low water content.

Calibration Procedure: Calibrate against Method no. 1.

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Parameter Measured: Water Content

Title of Test Method: Infrared Oven

Principle of Test Method: This method determines the water content of a soil by first weighing it wet and then again after it has been dried in the oven.

Test Method

(1) Apparatus: Infrared oven suitable for drying, balance, specimen containers.

(2) Procedure: The procedure for this method is the same as that for the Standard Oven-Dry method. That is, a specimen is placed wet onto a balance and weighed. It is then placed in an infrared oven and dried completely. It is then weighed again. The weight difference was the water content.

(3) Reference: N/A

Limitations: There are necessary safety precautions when using an infrared oven. Infrared ovens are generally not widely available.

Status of the Method: This method is not commonly used. It can yield rapid results, however. The method should be desirable to a large operation where the benefits of rapid results outweigh the costs of the limitations above and the initial investment.

Calibration Procedure: Calibrate against Method No. 1.

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

93-29041331

Method No. 8

Parameter Measured: Unit Weight

Title of Test Method: Standard Laboratory Volumetric

Principle of Test Method: This method determines the unit weight of an undisturbed soil sample by measuring the weight and volume.

Test Method

(1) Apparatus: Sampling tools, balance, water bath, volume measuring device, oven and coating material (e.g. paraffin).

(2) Procedure: This method of test is intended to determine the density of cohesive soil in the natural state, compacted cohesive soil, and stabilized soil by measuring the weight and volume of undisturbed samples. The method briefly consists of cutting out a block of soil, coating it with a known amount of paraffin, weighing to obtain the net weight of the sample and immersing in an overflow volumeter to determine the net volume of the sample, then dividing through for the unit weight.

(3) Reference: AASHTO T 233.

Limitations: The method is suitable for any material that remains intact during sampling. This method is particularly adaptable to irregularly shaped specimens and soil containing gravel, shells, etc. Sample size is not limited; large samples with coarse aggregate can be tested. This method is time consuming.

Status of the Method: This method is a nonstandard test when used in relation to compaction control. However, periodic record sampling on compacted embankments for dams usually entails obtaining block samples. In addition, if the sample is properly removed from the fill, this test provides for index and engineering properties.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the sample's net weight and net volume. An example data sheet is provided.

93129041332

ORDER NO. _____

CLIENT'S NO. _____

DATE _____

UNIT WEIGHTS

PROJECT _____ LOCATION _____ TESTED BY _____

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS ($w_w = w - w'$)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS ($w_s = w' - w''$)						
% MOISTURE, ($w = w_w / w_s \times 100$)						
DRY UNIT WT. LBS./FT.^{3}						

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS ($w_w = w - w'$)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS ($w_s = w' - w''$)						
% MOISTURE, ($w = w_w / w_s \times 100$)						
DRY UNIT WT. LBS./FT.^{3}						

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS ($w_w = w - w'$)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS ($w_s = w' - w''$)						
% MOISTURE, ($w = w_w / w_s \times 100$)						
DRY UNIT WT. LBS./FT.^{3}						

9 3 1 2 9 0 4 1 3 3 3

Parameter Measured: Unit Weight

Title of Test Method: Standard Laboratory Displacement

Principle of Test Method: This method determines the unit weight of a soil sample by determining the weight of the sample and the volume of its hole.

Test Method

(1) Apparatus: Sampling tools, soil tray and pans, balances, measure, drying equipment, two gallons of lubricating oil, and a gauge point.

(2) Procedure: This method determines the density of soil in-place by finding the mass and moisture content of a disturbed sample and measuring the volume occupied by the sample using oil of a known density. The method can be performed fairly fast; however, a chief concern is the messiness caused by the oil. The general procedure consists of leveling the test site, digging a hole in the compacted earthwork, weighing the material removed, measuring the volume of the hole by placing a measured quantity of oil in it and calculating the wet unit weight by dividing the weight of the moist soil by the volume of the hole.

(3) Reference: AASHTO T 214.

Limitations: This method may be used in testing materials with both fine and coarse particles; however, the test is best suited for soils and soil-aggregate mixtures that are relatively impervious. The method may not be suitable for testing materials having fissures, cracks, or large voids.

Status of the Method: The oil displacement method is a conventional test in the control of earthwork construction. However, it often provides less satisfactory results than the sand-cone method.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of the oil. No example data sheet is provided.

93129041334

Parameter Measured: Unit Weight

Title of Test Method: Standard Field Sand-Cone

Principle of Test Method: This method determines unit weight by determining the weight of a soil sample and the volume of its hole.

Test Method

(1) Apparatus: One-gallon jar, double cone assembly, baseplate and accessories.

(2) Procedure: The test consists of digging out a sample of the material to be tested and weighing it. The volume of the hole is then determined by using the sand-cone.

(3) Reference: ASTM D 1556.

Limitations: The sand-cone has features which limit its usefulness. The method can be used satisfactorily, however, if its limitations are recognized and proper precautions observed. The poured density of sand is affected by atmospheric moisture and change in relative humidity; thus, the sand should be calibrated before use. Care should be exercised to avoid jarring and densifying the sand during the filling procedure, and the test should not be conducted during vibration of the site, such as by heavy equipment. Sample size is limited by sand supply.

Status of the Method: The sand-cone test is a conventional test method for earthwork control. The method is reliable and a commonly used test to determine the density of in-place soil. On Corps of Engineers earthwork projects the test serves as the referee test for all other control tests used. The sand-cone test is widely used in cohesive soils and can be also used in soils of low plasticity, including gravelly soils. The test is not applicable in clean sands or gravels or loose granular materials. The method is applicable to large and small projects.

Calibration Procedure: Calibrate against Method No. 8, 9, or 10.

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of the sand. No example data sheet is provided.

93 1 29041335

Parameter Measured: Unit Weight

Title of Test Method: Standard Field Rubber Balloon

Principle of Test Method: This method determines unit weight by determining the weight of a soil sample and the volume of its hole.

Test Method

(1) Apparatus: Calibrated vessel, elastic membrane, pressure control device, baseplate and accessories.

(2) Procedure: This method is used for determining the in-place density by removing soil from a hole, weighing the excavated material, and measuring the volume of the hole by a liquid-filled (water) balloon under constant pressure. Chief advantages of the test are its operational simplicity and the speed with which tests can be conducted.

(3) Reference: ASTM D 2167.

Limitations: For general use in clays and consolidated sands, the rubber balloon apparatus provides good results. The method is not suitable for very soft soil which will deform under slight pressure or in which the volume of the hole cannot be maintained at a constant value. The method is not well adapted to the measurement of volumes in loose granular material. However, of all in-place density tests some soil engineers recommend the water balloon as the preferred method for granular soils. The test is well adapted to small and large projects. Physical limitation of the apparatus restricts the size of the test hole to approximately four or six inches in diameter and from six to twelve inches in depth.

Status of the Method: The water balloon test is widely used for determining in-place density for the control of earthwork. The method is used by the Corps of Engineers and other agencies because of its application to a wide range of materials and its past performance record.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of water. No example data sheet is provided.

Method No. 12

Prameter Measured: Unit Weight

Title of Test Method: Standard Field Drive-Cylinder

Principle of Test Method: This method determines the unit weight of a soil sample by securing one in a known-volume tube and then weighing it.

Test Method

(1) Apparatus: Acceptable drive cylinder, drive head, straightedge, shovel, weight, scales, drying oven and airtight containers.

(2) Procedure: The drive-cylinder method for determining in-place density involves obtaining a relatively undisturbed soil sample by driving a thin-walled cylinder into the soil with a special driving head. Two procedures are described in ASTM D 2937 for performing this test, one for testing at the surface or at very shallow depths, usually less than 3 ft (1 m), and one for testing at greater depths. The general procedure for both depths consists of driving a sampling tube into the soil, withdrawing the tube with sample, trimming sample flush with ends of tube, weighing, then calculating the unit weight of the soil by dividing the net weight of the sample by the volume of the tube.

(3) Reference: ASTM D 2937.

Limitations: The drive-cylinder method of determining in-place density can be used satisfactorily in moist, cohesive, fine-grained soils and in many sands which exhibit tendencies toward cohesiveness. The method is not appropriate for sampling very hard soils which cannot be penetrated easily, or for soils of low plasticity which are not readily retained in the cylinder. The destructive method sample size is limited by the sample tube. The chief disadvantage of the test is that its limited to fine-grained soils.

Status of the Method: The standard field drive-cylinder method is a conventional test method in earthwork control. It is, however, less accurate than the sand cone or water balloon methods.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the soil sample's weight. No example data sheet is provided.

93129041337

Method No. 13

Parameter Measured: Unit Weight

Title of Test Method: Standard Nuclear Moisture/Density Gage

Principle of Test Method: This method determines unit weight by a gamma source and a gamma detector.

Test Method

(1) Apparatus: A nuclear source emitting gamma rays, a gamma ray detector and a counter.

(2) Procedure: This method describes determination of the density of soil and soil-aggregate in place through the use of nuclear equipment. In general, the total or wet density of the material under test is determined by placing a gamma source and a gamma detector either on, into, or adjacent to the material under test. These variations in test geometry are presented as the backscatter, direct transmission, or air gap approaches. The intensity of radiation detected is dependent in part upon the density of the material under test. The radiation intensity reading is converted to measured wet density by a suitable calibration curve. Some commonly used sources of gamma rays are radium, cobalt 60 and cesium 137.

(3) Reference: ASTM D 2922

Limitations: The method described is useful as a rapid, nondestructive technique for the in-place determination of the wet density of soils and soil-aggregates. The fundamental assumptions inherent in the method are that Compton scattering is the dominant interaction and that the material under test is homogeneous. Test results may be affected by chemical composition, sample heterogeneity, and the surface texture of the material being tested. The technique also exhibits spatial bias in that the apparatus is more sensitive to certain regions of the material under test. The nuclear method, applicable to a wide range of soil, requires a considerable experienced operator to obtain reliable measurements. A weakness in the nuclear method, being nondestructive, is that a sample is not provided to determine the water content with which the test can be compared. In addition this method requires equipment that utilizes radioactive materials which may be hazardous to the health of the user. Effective operator instructions together with routine safety procedures are an essential part of the operation of equipment of this type.

Status of the Method: Nuclear gages offer a rapid and accurate means for obtaining density values for a wide variety of materials. Recent advances in the design of nuclear equipment and a better understanding of the nuclear principles involved have led to increasingly widespread use of nuclear gages in earth construction control work.

Calibration Procedure: The apparatus must be calibrated against a reliable direct method.

Documentation of Test: Items to be recorded include the counter's gamma ray counts. No example data sheet is provided.

Parameter Measured: Specific Gravity

Title of Test Method: Standard Laboratory

Principle of Test Method: This method determines the specific gravity of a soil sample by the use of a pycnometer.

Test Method

(1) Apparatus: A pycnometer and a balance.

(2) Procedure: The procedure for this method is to procure a soil sample, weigh it with the balance, and then determine its specific gravity by the use of the pycnometer.

(3) ASTM D 854

Limitations: N/A

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the sample weight and the pycnometer reading. An example data sheet is provided.

Name: _____ Sample Number: _____

Date: _____ Sheet Number _____

SPECIFIC GRAVITY DETERMINATIONS

Sample Number _____ Date: _____

Pycnometer Bottle Number: _____ Evap. Dish No. _____

Wt. Bottle + Water + Sample $= W_s =$ _____ Wt. Sample + Dish Dry = _____

Temperature of Suspension $= T =$ _____ Weight of Dish = _____

Wt. Bottle + Water at temp. $T = W_w =$ _____ Dry Wt. of Soil W_o = _____

$$e = \frac{W_o}{W_o + W_w - W_s} = \_\_\_\_ = \_\_\_\_ = \_\_\_\_$$

Remarks: _____

Sample Number _____ Date: _____

Pycnometer Bottle Number: _____ Evap. Dish No. _____

Wt. Bottle + Water + Sample $= W_s =$ _____ Wt. Sample + Dish Dry = _____

Temperature of Suspension $= T =$ _____ Weight of Dish = _____

Wt. Bottle + Water at temp. $T = W_w =$ _____ Dry Wt. of Soil W_o = _____

$$e = \frac{W_o}{W_o + W_w - W_s} = \_\_\_\_ = \_\_\_\_ = \_\_\_\_$$

Remarks: _____

Sample Number _____ Date: _____

Pycnometer Bottle Number: _____ Evap. Dish No. _____

Wt. Bottle + Water + Sample $= W_s =$ _____ Wt. Sample + Dish Dry = _____

Temperature of Suspension $= T =$ _____ Weight of Dish = _____

Wt. Bottle + Water at temp. $T = W_w =$ _____ Dry Wt. of Soil W_o = _____

$$e = \frac{W_o}{W_o + W_w - W_s} = \_\_\_\_ = \_\_\_\_ = \_\_\_\_$$

Remarks: _____

93129041341

Parameter Measured: Grain-Size Distribution

Title of Test Method: Standard Sieve Analysis (+200 Fraction)

Principle of Test Method: This method determines the +200 fraction of a soil sample by the use of a No. 200 sieve.

Test Method

(1) Apparatus: A No. 200 sieve, that is a sieve with 200 openings per inch, and balance.

(2) Procedure: This is a method-dependent test. A dried soil sample is weighed, poured onto a No. 200 sieve, and shaken. That amount of soil not passing through the sieve is the +200 fraction. The +200 fraction is then weighed on the balance.

(3) Reference: ASTM D 422.

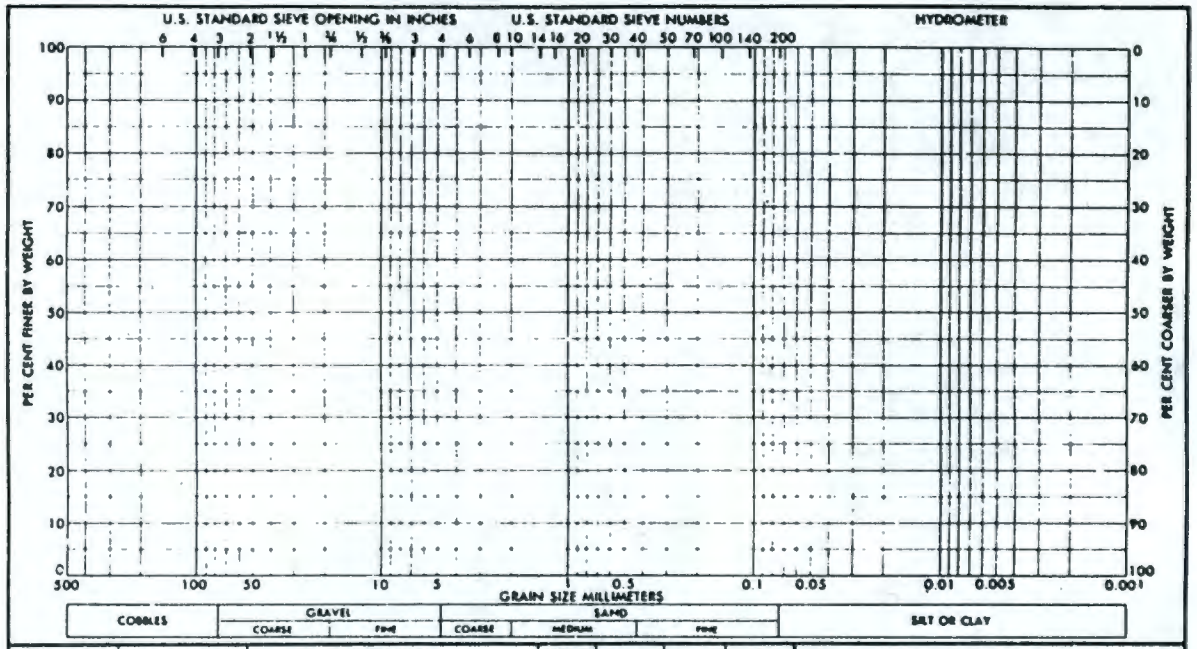
Limitations: The limitations of the method are its possible sources of error. These include: (a) overloading the sieve; (b) inadequate or incorrect shaking; and (c) broken or damaged sieves.

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the weight of the dried soil sample and the weight of the +200 fraction. An example data sheet is provided.

93129041342



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

PROJECT

AREA

BORING NO

DATE

GRADATION CURVES

ENG FORM 2087
1 MAY 63

REPLACES WES FORM NO 1241, SEP 1963, WHICH IS OBSOLETE

U.S. GOVERNMENT PRINTING OFFICE

Parameter Measured: Grain-Size Distribution

Title of Test Method: Amount of Soil Finer than No. 200 Screen (Wash) Standard

Principle of Test Method: This method determines the -200 fraction of a soil sample by the use of a No. 200 sieve and washing.

Test Method

(1) Apparatus: A No. 200 sieve and a balance.

(2) Procedure: This method is similar to that described for determining the +200 fraction. However if the soil sample to be tested contains plastic fines, drying will cause them to adhere to the fine sand grains, and the test will yield erroneous results. The solution is to weigh the dry sample beforehand. Pour it on the No. 200 screen. Wash the sample to loosen the fines and allow them to pass through the sieve. Dry that amount of soil remaining on the No. 200 screen and weigh it. The two weight differences is then the fines content.

(3) Reference: ASTM D 1140.

Limitations: The significant limitation of this method is the extra time required for washing and redrying.

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample and the dry weight of the +200 fraction. No example data sheet is provided.

Parameter Measured: Grain-Size Distribution

Title of Test Method: Standard Laboratory Hydrometer (-200 fraction)

Principle of Test Method: This method determines the grain-size distribution of the -200 fraction of a soil sample by the use of Stokes' Law and a standardized hydrometer.

Test Method

(1) Apparatus: A No. 200 sieve, a standardized hydrometer, a sedimentation cylinder, a thermometer and a beaker.

(2) Procedure: This method determines the grain-size distribution of that fraction of a soil sample passing the No. 200 sieve (the -200 fraction). The method utilizes a deflocculating (dispersing) agent and Stokes' law to enable the different particle sizes to settle at different rates, thus enabling the technician to determine their distribution.

(3) Reference: ASTM D 422.

Limitations: An experienced technician is required to perform this test method. Considerable time is required for sample preparation. The test itself requires several hours to perform.

Status of the Method: This is the standard method. As it is the only "exact" method for determining the percent silt sizes and the percent clay clay sizes, it is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample and the dry weights of the settled fractions. Example data sheets are provided.

9 3 1 2 9 0 4 1 3 4 5

HYDROMETER ANALYSIS

Date _____

Project _____

Boring No. _____

Sample or Specimen No.	Classification	
Dish No.	Graduate No.	Hydrometer No.

Dispersing agent used _____ , Quantity _____

Dispersing agent correction, C_d = _____ ; Meniscus correction, C_m = _____

Time	Elapsed Time min	Temp °C	Hydro. Reading (R')	Corrected Reading (R)	Particle Diameter (D), mm	Temp Correction (m)	$R - C_d + m$	Percent Finer	
								Partial	Total

Weight in grams			
	Dish plus dry soil		
	Dish		
	Dry soil	W_o	

Specific gravity of solids, G_s = _____

Corrected hydrometer reading (R) = hydrometer reading (R') + C_m

The particle diameter (D) is calculated from Stoke's equation using corrected hydrometer reading. Use nomographic chart for solution of Stoke's equation.

Hydrometer graduated in specific gravity

$$\text{Partial percent finer} = \frac{G_s}{G_s - 1} \times \frac{100}{W_o}(R - C_d + m)$$

Hydrometer graduated in grams per liter

$$\text{Partial percent finer} = \frac{100}{W_o}(R - C_d + m)$$

$$\text{Total percent finer} = \text{partial percent finer} \times \frac{W_s - W_1}{W_s}$$

W_s = total oven-dry wt of sample used for combined analysis

W_o = oven-dry wt in grams of soil used for hydrometer analysis

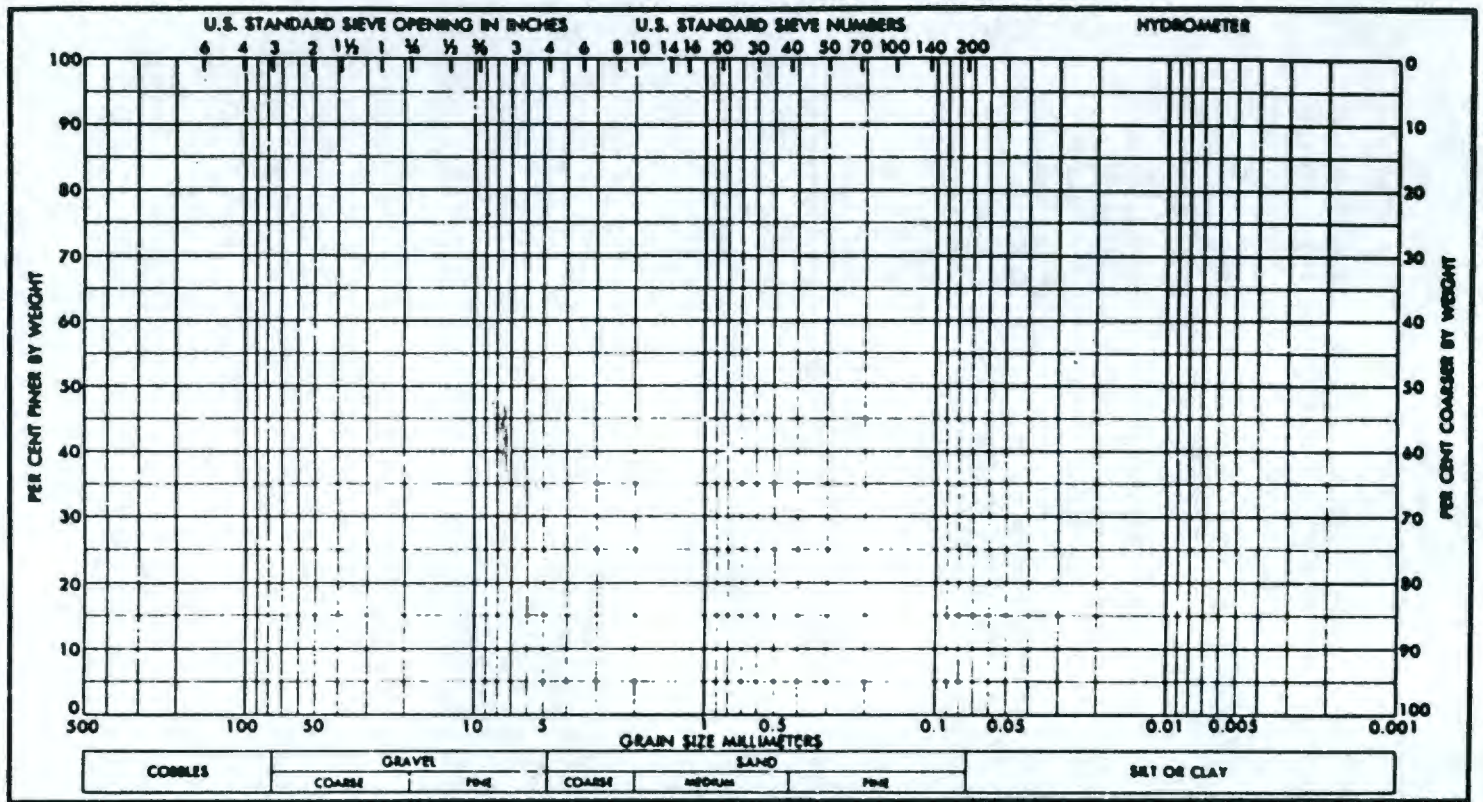
W_1 = oven-dry wt of sample retained on No. 200 sieve

Remarks _____

Technician _____ Computed by _____ Checked by _____

ENG FORM 1 JUN 66 3842 D41488

9 3 1 2 9 0 4 1 3 4 7



SAMPLE NO	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

PROJECT

AREA

BORING NO

DATE

GRADATION CURVES

ENG FORM 1 MAY 63 **2087** REPLACES WES FORM NO 1241, SEP 1962, WHICH IS OBSOLETE

U.S. GOVERNMENT PRINTING OFFICE 1966 OF—700-100

Parameter Measured: Grain-Size Distribution

Title of Test Method: Pipette Method for Silt and Clay Fraction

Principle of Test Method: This method determines the silt and clay fractions of a soil sample by the use of a dispersing agent, Stokes' law, and a pipette.

Test Method

(1) Apparatus: A No. 200 sieve, a beaker and a pipette.

(2) Procedure: The soil sample is deflocculated in a dispersing agent for one hour. The soil-water-agent mixture is then agitated and allowed to sit. Theroretically all the sand and silt sizes will have settled by then. The water, with the suspended clay sizes, is then drawn off by the pipette. The settled fraction is the original soil sample minus the clay fraction. The settled fraction is completely dried and passed through a No. 200 sieve. The fraction passing is the silt fraction; the fraction remaining is the sand fraction.

(3) Reference: Mills, 1970.

Limitations: The method is less exact than the standard laboratory hydrometer method.

Status of the Method: The method lends itself well to field laboratory use and is widely accepted.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample, the dry weight of the settled fraction and the dry weight of the silt fraction. No example sheet is provided.

9 3 1 2 9 0 4 1 3 4 8

Method No. 19

Parameter Measured: Grain-Size Distribution

Title of Test Method: Decantation Method for Silt and Clay Fraction

Principle of Test Method: This method determines the silt and clay fractions of a soil sample by the use of a dispersing agent, Stokes' law and decantation.

Test Method

(1) Apparatus: A No. 200 sieve and a beaker.

(2) Procedure: The soil sample is deflocculated in a dispersing agent for one hour. The soil-water-agent mixture is then agitated and allowed to sit. Theoretically all the sand and silt sizes will have settled by then. The water, with the suspended clay sizes, is then drawn off by decantation (careful pouring). The settled fraction is the original sample minus the clay fraction. The settled fraction is completely dried and passed through a No. 200 sieve yielding the silt fraction.

(3) Reference: Mills, 1970.

Limitations: The method is less exact than the standard laboratory hydrometer method. As is also more rudimentary than the pipette method, it can be less accurate than this method in execution.

Status of the Method: The method lends itself well to field laboratory use and is widely accepted.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weights of the sample, the settled fraction and the silt fraction. No example sheet is provided.

9 3 1 2 9 0 4 1 3 4 9

Method No. 20

Parameter Measured: Liquid Limit

Title of Test Method: Standard Multipoint

Principle of Test Method: This method determines the liquid limit of a soil sample by the use of the liquid limit device and a minimum of three trials.

Test Method

(1) Apparatus: Evaporating dish, spatula, liquid limit device, grooving tool and balance.

(2) Procedure: A soil sample is air dried. Distilled water is added and mixed thoroughly with the sample till it is ready to be tested. A sample is placed in the liquid limit device and divided by the grooving tool. The test is run till the soil halves meet. The result is plotted. A minimum of three trials are performed.

(3) Reference: ASTM D 423.

Limitations: The method requires considerable time and a laboratory environment to be performed.

Status of the Method: The standard multipoint method is used for acceptance or rejection of material or where a high degree of accuracy is required.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry weight of the sample, the water content and the number of blows. An example data sheet is provided.

LIQUID AND PLASTIC LIMIT TESTS

For use of this form, see EM 1110-1-2906.

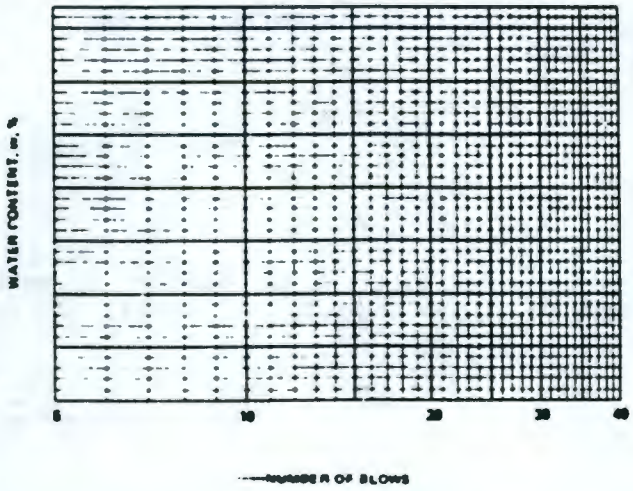
DATE _____

PROJECT _____

BORING NO. _____ SAMPLE NO. _____

LIQUID LIMIT

RUN NO.	1	2	3	4	5	6
TARE NO.						
WEIGHT IN GRAMS: TARE PLUS WET SOIL						
WEIGHT IN GRAMS: TARE PLUS DRY SOIL						
WEIGHT IN GRAMS: WATER W_w						
WEIGHT IN GRAMS: TARE						
WEIGHT IN GRAMS: DRY SOIL W_s						
WATER CONTENT, % w						
NUMBER OF BLOWS						



LL _____

PL _____

PI _____

Symbol from plasticity chart

_____

PLASTIC LIMIT

RUN NO.	1	2	3	4	5	NATURAL WATER CONTENT
TARE NO.						
WEIGHT IN GRAMS: TARE PLUS WET SOIL						
WEIGHT IN GRAMS: TARE PLUS DRY SOIL						
WEIGHT IN GRAMS: WATER W_w						
WEIGHT IN GRAMS: TARE						
WEIGHT IN GRAMS: DRY SOIL W_s						
WATER CONTENT, % w						
PLASTIC LIMIT						

REMARKS _____

TECHNICIAN _____ COMPUTED BY _____ CHECKED BY _____

ENG FORM 1 JUN 66 3838

U.S. GPO 1984-0-482-064/10004

93129041351

Parameter Measured: Liquid Limit

Title of Test Method: Standard One Point

Principle of Test Method: This method determines the liquid limit of a soil sample by the use of the liquid limit device and one trial.

Test Method

(1) Apparatus: Same as Method 20.

(2) Procedure: Same as Method 20, except that only one test is performed and a simple formula is used to calculate the liquid limit.

(3) Reference: ASTM D 423.

Limitations: The method requires considerable time and a laboratory environment to be performed.

Status of the Method: For the purposes needed at a hazardous waste disposal facility the standard one point method will yield reasonable data and is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry weight of the sample, the water content and the number of blows. No example data sheet is provided.

Parameter Measured: Plastic Limit

Title of Test Method: Standard Laboratory

Principle of Test Method: This method determines the plastic limit of a soil sample, that is the lowest water content at which the soil can be rolled into 1/8 in. threads without breaking.

Test Method

(1) Apparatus: Evaporating dish, spatula, suitable containers, and balance.

(2) Procedure: For a given soil sample begin at a water content estimated to be greater than the plastic limit. A good start point would be somewhat below the approximate liquid limit. Shape the soil into an ellipsoidal mass. Roll the sample into 1/8 in. threads. Cut the threads into 6 to 8 pieces. Repeat the process till the threads break at 1/8 in. An oven-dry moisture content determination at that point will yield the plastic limit.

(3) Reference: ASTM D 424.

Limitations: The method is simple and straightforward.

Status of the Method: This is the standard method and is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry and wet weight of the sample at the plastic limit. An example data sheet is provided.

93129041353

LIQUID AND PLASTIC LIMIT TESTS

For use of this form, see ER 1110-1-1906.

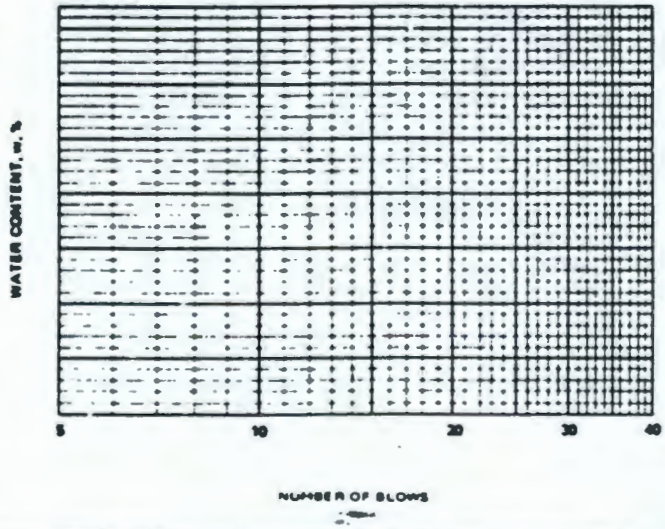
DATE _____

PROJECT _____

BORING NO. _____ SAMPLE NO. _____

LIQUID LIMIT

	RUN NO.	1	2	3	4	5	6
	TARE NO.						
WEIGHT IN GRAMS	TARE PLUS WET SOIL						
	TARE PLUS DRY SOIL						
	WATER W_w						
	TARE						
	DRY SOIL W_s						
	WATER CONTENT, % w						
	NUMBER OF BLOWS						



LL _____

PL _____

PI _____

Symbol from plasticity chart _____

PLASTIC LIMIT

	RUN NO.	1	2	3	4	5	NATURAL WATER CONTENT
	TARE NO.						
WEIGHT IN GRAMS	TARE PLUS WET SOIL						
	TARE PLUS DRY SOIL						
	WATER W_w						
	TARE						
	DRY SOIL W_s						
	WATER CONTENT, % w						
	PLASTIC LIMIT						

REMARKS _____

TECHNICIAN _____ COMPUTED BY _____ CHECKED BY _____

ENG FORM 1 JUN 65 3838

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Standard Unconfined Compression

Principle of Test Method: This method uses a compression device to determine the unconfined compressive strength of a soil sample: that is the load per unit area at which the specimen fails in simple compression.

Test Method

(1) Apparatus: Compression device, sample ejector, deformation indicator, vernier caliper, timer, balance and oven.

(2) Procedure: An undisturbed sample is secured and a specimen prepared as per the reference. An estimate of the failure is made based on experience with a similar material. The specimen is placed in compression by uniformly progressive loads at 30 second intervals till failure or 20% strain is reached. The results are plotted.

(3) Reference: ASTM D 2166.

Limitations: The method requires a lab[illegible]tory environment, the securing of an undisturbed sample (as described by [illegible] Method D 1587), considerable specimen preparation, calculations and considerable time.

Status of the Method: The method is the standard means for unconfined compressive strength determination. However because of its limitations it is not commonly used in process control (because of more efficient methods) but is widely used in acceptance testing.

Calibration Procedure: The deformation indicator must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the moisture content of the sample as well as the strain deformations at their respective loads. An example data sheet is provided.

UNCONFINED COMPRESSION TEST - DATA SHEET

Soil Description _____ Project _____

_____ Laboratory _____

Boring No. _____ Surface Elev. _____ Sample No. _____ Sample Depth Interval _____

LL _____ % w _____ % PL _____ % Date Tested _____

Pocket Penetrometer, P.P. _____ tsf Specific Gravity, G_s _____ Dry Unit Weight, γ_d _____ pcf

Soil Specimen Measurements

Diameter _____ in. Initial Area, A_o: _____ sf Initial Length, L_o: _____ in.

Proving Ring Conversion Factor _____ Corrected Area, $A_c = \frac{A_o}{1 - \varepsilon}$

WATER CONTENT

Specimen Location	Top	Middle	Bottom	Entire Remolded Sample
Container No.				
Wt. Cont. + Wet Soil (gms.)				
Wt. Cont. + Dry Soil (gms.)				
Wt. Container (gms.)				
Wt. Dry Soil (gms.)				
Wt. Water (gms.)				
Water Content (%)				

COMPRESSION TEST

Elapsed Time (Min.)	Load Dial Reading	Load (lbs.)	Vert. Dial (inches)	Axial Strain ε (%)	Corr. Area, A_c (sf)	Comp. Stress S_c (psf)

Method No. 24

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Field Expedient Unconfined Compression

Principle of Test Method: This method uses a field expedient compression device to determine the unconfined compressive strength of a soil sample.

Test Method

(1) Apparatus: Sample ejector, compression device, stress and deformation indicators, balance, oven and trimmer.

(2) Procedure: A sample is secured and prepared. An estimate of the samples failure strength is made based on experience with a similar material. The specimen is then placed in compression by uniformly progressive loads till failure or a predetermined percent strain is achieved. The results are plotted.

(3) Reference: TM 5-530, 1971 (U. S. Army).

Limitations: The method involves a procedure virtually identical to that called for in the standard laboratory method. However the apparatus used in the field expedient method is less accurate, less care is given to sample preparation and the method itself is less accurate.

Status of the Method: The method lies between the standard laboratory method and the hand device methods in terms of accuracy and resources required. The standard laboratory method is the accepted method for laboratory needs, and the hand devices are sufficient for field testing. This method is not widely used.

Calibration Procedure: The stress and strain indicators must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the samples moisture content as well as the stress and strain readings. No example data sheet is provided.

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Hand Penetrometer

Principle of Test Method: This method uses the hand penetrometer to determine the unconfined compressive strength of a soil sample.

Test Method

(1) Apparatus: Hand penetrometer with stress and strain indicators, trimming knife.

(2) Procedure: A sample is taken and trimmed by the hand penetrometer and a trimming knife. The test is then run with the device. One man can run the device and read the various stress and strain indicators. These values can be plotted and the unconfined compressive strength determined.

(3) Reference: Hvorslev, 1948.

Limitations: The sampling operation may cause a slight disturbance and decrease in strength of very brittle soils, a small downward deflection of soft soils, and a slight compaction of loose and partially saturated soils.

Status of the Method: The determination of cohesive soil consistency classification by this method is widely used as it is more accurate than the visual-manual method, and although it is less accurate than the standard laboratory method it is quite sufficient given the broad classifications for cohesive soil consistency.

Calibration Procedure: The stress and strain indicators must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the stress and strain readings during testing. An example data sheet is provided.

UNCONFINED COMPRESSION TEST

Soil Description _____ Project _____

_____ Laboratory _____

Boring No. _____ Surface Elev. _____ Sample No. _____ Sample Depth Interval _____

LL _____ % w _____ % PL _____ % Date Tested _____

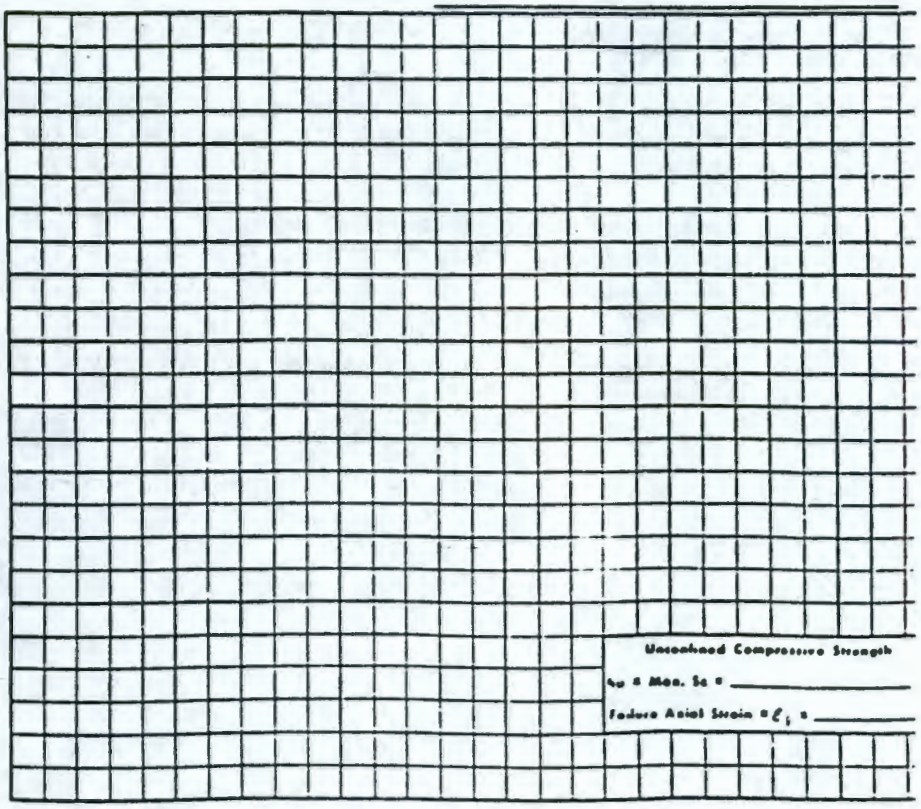
Pocket Penetrometer, P.P. _____ tsf Specific Gravity, G_s _____ Dry Unit Weight, γ_d _____ pcf

Axial Strain Rate: _____ inch/min.

Diagram of Failure:

Grain Size Distribution				
%Gr.	%C.S.	%F.S	% Silt	% Clay

Remarks: _____



9 3 1 2 9 0 4 1 3 5 9

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Hand-held Torvane

Principle of Test Method: This method uses a hand-held torvane to determine the soil shear strength of the in situ soil.

Test Method

(1) Apparatus: Hand-held torvane with gage.

(2) Procedure: The handheld torvane is pushed through the soil crust to the desired depth. A rotary motion is then applied to the handle. The gage values are read and the soil shear strength, values for cohesion and the internal angle of friction, and consistency classification can be determined.

(3) Reference: Lanz, 1968.

Limitations: The method is standardized and the values gained from the method can be correlated to the standard laboratory method for unconfined compressive strength. However the method is somewhat less accurate than others.

Status of the Method: The torvane is the most widely accepted of the shear vane devices. Since it yields in situ values rapidly it is widely used.

Calibration Procedure: The gage must be zeroed before testing.

Documentation of Test: Items to be recorded include the gage readings. No example data sheet is included.

Method No. 27

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: 25 Blow Standard Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test. This is the original Proctor test.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The specimen is prepared and placed in a mold. Most commonly the mold is the 4 inch mold. The soil is placed in three like layers. Each layer is compacted. Most commonly the compaction is 25 blows with a 5.5 pound hammer dropping 12 inches. Following compaction of all three layers the specimen is removed from the mold and trimmed. The mass of the sample is determined. This is divided by the volume of the mold and the wet density of the sample, in pcf, is determined. The moisture content of the sample is then determined by oven drying. This entire procedure is repeated for at least four specimens. The four specimens' moisture contents should vary by about 1-1/2% between each sequential sample. The specimen moisture contents should bracket the estimated optimum moisture content. The values are plotted along with the "zero air voids curve." The optimum moisture content and maximum density of the sample can then be determined.

(3) Reference: ASTM D 698.

Limitations: This method requires a laboratory environment, the considerable time involved in sample drying and several hours to perform the test itself.

Status of the Method: This is the standard method. It is widely used. It is suited for the lesser compactive effort as might be applied to trench backfill. It may not be as suitable as the modified method for higher compactive efforts such as in the trench floor.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. An example data sheet is provided.

COMPACTION TEST

Date _____

Project _____

Boring No. _____ Sample No. _____

Mold No.	inch diam mold	Volume of mold, V, in cc =
Mold constant, C = 62.4 ÷ V =		Initial water content, w_o =

blows per each of layers, with lb rammer inch drop

Specimen No.							
Preparation of specimen							
$100 + w_o$							
Weight in grams: Oven-dry soil	W'_s						
Wet soil = $\frac{W'_s(100 + w_o)}{100}$	W'_o						
Tare							
Tare plus wet soil							
Test water content	w	%	%	%	%	%	%
Water added = $\frac{W'_s(w' - w_o)}{100}$ in cc							
Compacted specimen							
Weight in grams: Mold plus wet soil							
Mold tare							
Wet soil	W						
Dry soil = $\frac{100\,W}{100 + w}$	W_s						
Water content = $\frac{W - W_s}{W_s} \times 100$	w	%	%	%	%	%	%
Unit wt, lb/cu ft: Wet unit wt = CW	γ_m						
Dry unit wt = CW_s	γ_d						
Water content determinations							
Specimen No.							
Tare No.							
Weight in grams: Tare plus wet soil							
Tare plus dry soil							
Water	W_w						
Tare							
Dry soil	W_s						
Water content = $\frac{W_w}{W_s} \times 100$	w	%	%	%	%	%	%

Remarks _____

Technician _____ Computed by _____ Checked by _____

ENG FORM 1 JAN 63 1843 D41501

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: 25 Blow Modified Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The specimen is prepared and placed in a mold in three like layers. The mold most commonly used is the four inch mold. Each layer is compacted. The compaction used for the four inch mold is 25 blows with a 10 pound hammer dropping 18 inches. Following compaction of all three layers the specimen is removed from the mold and trimmed. The mass of the sample is determined. This is divided by the volume of the mold and the wet density of the sample, in pcf, is determined. The moisture content of the sample is then determined by oven drying. The entire procedure is repeated for at least four specimens. The four specimens' moisture contents should vary sequentially by about 1-1/2 percent. The specimen moisture contents should bracket the estimated optimum moisture content. The values are plotted along with the "zero air voids curve." The optimum moisture content and maximum density of the sample can then be determined.

(3) Reference: ASTM D 1557.

Limitations: This method requires a laboratory environment, the considerable time involved in sample drying and several hours to perform the test itself.

Status of the Method: This is also a standard method. It is widely used. As it better represents greater compactive effort than does the original Proctor test, it is more suitable for process control testing for trench floors and the like.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

93129041363

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Nonstandardized Proctor Compaction

Principle of Test Method: These methods determine the optimum moisture content and the maximum density of a soil sample by kneading compaction, static compression or other devices.

Test Method

(1) Apparatus: Molds, sieves, balance, drying oven, extruder, kneading device or static compression device.

(2) Procedure: The procedures are method specific. (See the references.) However the procedures are very similar to the standard laboratory methods. Only the nature of the compactive effort and the specifics of the mold size, etc., differ.

(3) Reference: Johnson and Sallberg, 1962; and Antrim, 1970.

Limitations: These methods require a laboratory environment, the considerable time involved in sample drying and several hours to perform the test themselves.

Status of the Method: These are not standard laboratory methods. They were developed for use in special situations. They are used by several state highway departments. They are not widely used in the laboratory because of the preference for the standard methods or in the field because of the ease and sufficiency of other methods.

Calibration Procedure: See the references.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Rapid, One Point Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test and estimation given one specimen test and derived value.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure is essentially the same as that for the standard laboratory method. However, rather than running four or more (usually the number is five) specimens through the test and deriving a like number of points, only one test and point are derived. The one point is at a moisture content estimated to be on the dry side of the optimum. From this point, and the well documented data on the soil, the optimum moisture content and maximum density can be determined.

(3) Reference: Department of the Army, 1977.

Limitations: This method depends upon good and well documented data on the local soils. The method also depends upon data which defines a relatively good line of optimums.

Status of the Method: For suitable soils this method provides a much more rapid means of process control. It is widely used. It is probable that this method could be sufficiently applied to the compaction of trench backfill.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Method No. 31

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Rapid, Two Point Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test and estimation given two specimen tests and derived values.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure is essentially the same as that for the standard laboratory method. However, rather than running four or more (usually the number is five) specimens through the test and deriving a like number of points, only two tests and points are derived. The first test is with a specimen estimated to be at the optimum moisture content or just on the dry side of the optimum. The second test is with a specimen 2 or 3 percentage points dry of the moisture content of the first specimen. From these points, and the well documented data on the soil, the optimum moisture content and maximum density can be determined.

(3) Reference: Department of the Army, 1977.

Limitations: This method depends upon good and well documented data on the local soils. The method also depends upon data which defines a relatively good line of optimums.

Status of the Method: In this method two curves are developed, as opposed to one curve in the one point method, thus this method can be expected to yield a better estimated curve. As this method provides more accuracy than the one point method, it too could be applicable to trench backfill compaction process control.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Hilf's Rapid

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by the standard impact compaction test of three samples, the use of standardized forms, and an estimate of the optimum moisture content.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure utilizes the standard impact compaction test. Three samples are tested. The first sample is that at field moisture, a moisture content estimated to be on the dry side of optimum. The second and third samples are tested at moisture contents two and four percent more than the field moisture. The derived values are compared to standardized forms and plotted. Without determination of water content, the maximum density and difference of the field moisture from the optimum content can then be determined. This is done by connecting the plotted points, which bracket the optimum moisture content, and thus yield its value.

(3) Reference: Hilf, 1970.

Limitations: This method is suitable for only low plasticity cohesive soils.

Status of the Method: When applicable this method yields sufficient data in much less time than the standard impact tests. However, because it yields only an approximation of the optimum moisture content its applicability by itself is limited.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Ohio Highway Department Nest of Curves*

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by the standard impact compaction test yielding one point and its placement on a nest of curves for like soils.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves, circular slide rule.

(2) Procedure: A single test is performed as per one of the standard impact compaction methods. The derived point is then matched to a nest of curves. For field expedience this nest of curves is often contained on a circular slide rule. The optimum moisture content and maximum density are then estimated from the appropriate curve.

(3) Reference: Ohio Highway Department, 1958.

Limitations: This method depends upon good and well documented data on the local soils.

Status of the Method: Where a family of curves exists this method is a rapid means of determining the optimum moisture content and maximum density. It has proven to be sufficient in a widespread history of usage.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

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* Many state highway departments have developed similar nests or sets of curves. Since these are based on local materials, they should be used where available.

0 6 2 4 1 3 6 8

Method No. 34

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Harvard Miniature

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by kneading compaction test with the Harvard Miniature device.

Test Method

(1) Apparatus: Molds, tamper, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure utilizes different apparatus than does the standard impact compaction test. Also this procedure utilizes kneading as opposed to impact compaction. Other than that, with the exception of specifics, the procedures are quite similar. This procedure is readily adaptable to better represent the actual field compactive effort.

(3) Reference: Wilson, 1970.

Limitations: This method is suitable only for soils passing the No. 4 screen. Thus it is applicable for use at a hazardous waste disposal facility.

Status of the Method: The method is small in terms of apparatus cost and size, simple, adaptable to duplicate the compactive effort achieved by larger equipment and ideal for field laboratory use. The kneading action of the Harvard Miniature apparatus is superior to the impact action of the impact devices.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

93129041369

Parameter Measured: Cohesionless Soil Relative Density

Title of Test Method: Standard Laboratory Maximum Density

Principle of Test Method: This method determines the maximum relative density of a cohesionless soil sample by the use of a vibratory table.

Test Method

(1) Apparatus: Vibratory table, molds, dial indicator, calibration bar, scale, other related equipment.

(2) Procedure: A soil sample is oven dried. The sample is thoroughly mixed. The sample is placed in a mold with a surcharge weight. The mold is vibrated for 8 minutes. The volume of the densified soil sample within the mold is determined. The sample is weighed. The maximum relative density can then be determined.

(3) Reference: ASTM D 2049.

Limitations: The method requires a vibratory table. This item is not often found on field sites.

Status of the Method: The method is the standard method and is widely used for laboratory purposes. The provision exists for a wet method in the reference.

Calibration Procedure: The exact mold volume must be determined and dial must be zeroed before the test.

Documentation of Test: Items to be recorded include the mold volume and dry weight of the sample. An example data sheet is provided.

RELATIVE DENSITY

MINIMUM AND MAXIMUM DENSITY DETERMINATIONS

DATE _____

PROJECT _____

BORING NO _____ SAMPLE NO _____

CLASSIFICATION

HOLD NO.	HOLD DIAMETER, IN.	HEIGHT OF HOLD, H_o, LB

VOLUME OF HOLD, V_o, CU FT	END AREA OF HOLD, A_o, SQ FT

MINIMUM DENSITY

TOTAL NO.			1	2	3	4
WEIGHT LB	HOLD (OR TARE) AND SOIL, DRY	w				
	HOLD (OR TARE)	w_o				
	SOIL, DRY	w_s				
MIN DRY DENSITY, LB/CU FT = w_s/V		γ_d				
MIN DRY DENSITY, AVERAGE			LB/CU FT			

MAXIMUM DENSITY

METHOD USED

TOTAL NO.			1	2	3	4
HEIGHT, IN.	LEFT DIAL READING	h_L				
	RIGHT DIAL READING	h_R				
	AVERAGE DIAL = $(h_L + h_R)/2$	h_{avg}				
	INITIAL DIAL READING	h_o				
	HEIGHT CHANGE = $h_o - h_{avg}$	Δh				
VOL CU FT	VOLUME CHANGE = $(\Delta h/12) \times A_o$	Δv				
	VOLUME OF SOIL = $V_o - \Delta v$	v				
WEIGHT LB	HOLD (OR TARE) AND SOIL, DRY	w				
	HOLD (OR TARE)	w_o				
	SOIL, DRY	w_s				
MAX DRY DENSITY, LB/CU FT = w_s/v		γ_d				
MAX DRY DENSITY AVERAGE			LB/CU FT				

REMARKS _____

TECHNICIAN _____ COMPUTED BY _____ CHECKED BY _____

ENG FORM NO 3850
REV JUNE 1970

PLATE XII-1

93129041371

Method No. 36

Parameter Measured: Cohesionless Soil Relative Density

Title of Test Method: Standard Laboratory Minimum Density

Principle of Test Method: This method determines the minimum relative density of a cohesionless soil sample by the standard method.

Test Method

(1) Apparatus: Molds, pouring devices, 3/8 in. sieve, and straightedge.

(2) Procedure: A soil sample is oven dried. The soil is segregated into a +3/8 in. and a -3/8 in. fraction by passing through the sieve. Each fraction is carefully poured to overflowing into pre-measured molds. The excess soil is screeded off. The soil fractions are weighed and the minimum relative density determined.

(3) Reference: ASTM D 2049.

Limitations: The method depends upon the technician's ability to carefully pour the segregated soil sample into the molds and his ability to screed off the excess with minimum effect to the soil in the molds.

Status of the Method: The method is the standard method and is widely used. It lends itself well to field site use.

Calibration Procedure: The exact mold volume must be determined before the test.

Documentation of Test: Items to be recorded include the mold volumes and the soil fraction weights. No example data sheet is provided.

Method No. 37

Parmater Measured: Cohesionless Soil Relative Density

Title of Test Method: Modified Providence

Principle of Test Method: This method determines the maximum relative density of a cohesionless soil sample by the use of a hammer.

Test Method

(1) Apparatus: Mold, dial indicator, hammer, balance.

(2) Procedure: A soil sample is oven dried and thoroughly mixed. It is placed in a mold and a surcharge weight equivalent to 1 psi is applied. The mold is struck uniformly by a hammer in the specified fashion till the dial reading changes less than 0.005 inches for any 25 blow cycle. The sample is then measured.

(3) Reference: Department of the Army, 1980.

Limitations: A nonuniform distribution of the hammer blows over the height and circumference of the mold may cause error in the determination of the maximum relative density.

Status of the Method: The method is not as accurate as the standard laboratory method. However, because no vibratory table is required and because the method's accuracy is sufficient for process control, the method is widely used at field sites.

Calibration Procedure: The exact mold volume must be determined and the dial must be zeroed before the test.

Documentation of Test: Items to be recorded include the mold volume and the dry weight of the sample after testing. No example data sheet is provided.

93129041373

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Bonded Seam Strength

Principle of Test Method: This method tests the seam strength of a specimen by placing it in tension and measuring its modulus of elasticity.

Test Method

(1) Apparatus: Grips, thickness gage, width-measuring devices, specimen cutter, extension indicators and a rate-of-jaw-separation testing machine.

(2) Procedure: A specimen of a bonded seam is cut and measured and placed in the machine perpendicular to the center line. The specimen is then placed in tension. The same is done for a specimen of the sheet itself. The tensile moduli of elasticity for both are calculated. The bonded seam strength can then be calculated as a percentage of the sheet strength.

(3) Reference: ASTM D 3083.

Limitations: The method requires a "sheltered" environment and significant accuracy to be valid. This requires a qualified test conductor and the apparatus described in a "sheltered" environment. A deficiency in any of these requirements would limit the validity of the method.

Status of the Method: This method is probably not applicable to all quality assurance programs for hazardous waste disposal facilities. The apparatus, "sheltered" environment and qualified test conductor may be too much for a small operation. The equipment needed is also expensive and another method might prove to be more economical. Modified methods, the results of which correlate to this standard method, have been developed and are proving acceptable. These modified methods do not require the "sheltered" environment or as elaborate apparatus.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading versus time and elongation versus time. No example data sheet is provided.

Method No. 39

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Breaking Strength

Principle of Test Method: This method tests the breaking strength of specimens by placing them in tension in two transverse directions till they break.

Test Method

(1) Apparatus: Straining mechanism, clamps for holding specimen, and load and elongation recording mechanisms.

(2) Procedure: At least ten specimens of a bonded seam should be cut and measured (if one of the tests is invalid another specimen must be tested to yield a total of ten tests). The specimens are placed longitudinally in the clamps and strained till they break. Specimens should be strained till breakage in both the parallel and perpendicular to the seam directions. The average of five valid tests is the breaking strength of the seam in that direction.

(3) Reference: ASTM D 751.

Limitations: The specimens can tear or slip at the clamps.

Status of the Method: This method is probably not applicable to all quality assurance programs for disposal facilities. The ten or more specimens required are considerable. The equipment needed is relatively expensive and very accurate. Electric power is required. However for a large operation the method may be applicable as it yields accurate, valid data in a short time.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading versus time, elongation versus time, and loading at breakage. No example data sheet is provided.

9 3 1 2 9 0 4 1 3 7 5

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Peel Adhesion

Principle of Test Method: This method tests the peel adhesion of a specimen by measuring the force it takes to peel apart a bonded seam.

Test Method

(1) Apparatus: A CRE or CRT-type, power driven, tension testing machine or a frame and mandrels for the Static-Mass Method.

(2) Procedure: A specimen of a bonded seam is cut and measured. At one end of the specimen the parts are separated. The separated parts are attached to the machine. The tension on the separated parts is increased till failure. All forces and separations are carefully measured.

(3) ASTM D 413.

Limitations: A CRE or CRT-type machine requires power. A frame and mandrels set is inexpensive but is also uncommon to many construction site field testing facilities. Tearing of one or both of the separate parts of the specimen during loading is a hazard.

Status of the Method: Because of its ease and simplicity this test is applicable to a quality assurance program for a hazardous waste disposal facility. The frame and mandrels set are inexpensive. The test method does not require a "sheltered" environment beyond what most construction site field testing facilities provide.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading forces versus time and separations versus time. No example data sheet is provided.

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Air Lance

Principle of Test Method: This method tests the bond of a seam by detecting anomalies with a jet of compressed air.

Test Method

(1) Apparatus: A source of compressed air (40-60 psi), a wand pipe narrow tip nozzle (e.g. 3/16 in.).

(2) Procedure: One man walks the length of the bonded seam, pointing the nozzle and air jet at the edge of the top flap, within one inch of the same, with the nozzle parallel to the edge. A bubble will form under any unbonded edges. The results of such a bubble will be both audible and visual.

(3) Reference: N/A

Limitations: The method should be conducted with specimen testing (see test methods 39, 40 and 41) to assure field seam integrity and reliability. The method may not detect small anomalies.

Status of the Method: The method is applicable to a quality assurance program as a relatively rapid and rough determination of seam integrity. It should be conducted along with specimen testing. Its advantages over methods 43 and 44 are its ease, speed and economy. Its disadvantage is its rough detection capability.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the detection and location, as well as marking of all anomalies. No example data sheet is provided.

9 3 1 2 9 0 4 1 3 7 7

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Vacuum Box

Principle of Test Method: The method detects leaks in the seam by means of a vacuum.

Test Method

(1) Apparatus: Vacuum pump, power plant, inspection box, vacuum guage, soap, gasket.

(2) Procedure: The seam is lathered with soap to form a tight fit with the gasket. The inspection box is passed over the seam and it will detect any leaks, including those of pinhole size. The method tests seam integrity by detecting leaks. It does not test seam strength.

(3) Reference: Copyright by American Pipe & Steel Corporation.

Limitations: This method was developed for testing metal tanks and other similar containers. Because it is labor intensive and because of the considerable time required the method does not lend itself to expedient seam integrity testing. The length of a particular seam, the seam edges, the weight of the equipment, the relative labor intensity and the steep slopes of trench walls are all pontentially troublesome.

Status of the Method: This method is applicable to a quality assurance program for a hazardous waste disposal facility, especially where the permittee wants a great degree of confidence in the seam integrity and impermeability. All the equipment can be purchased for less than $1000. But as it requires a two man crew and covers 5 to 6 feet per minute it can be costly in labor costs and construction time. This method is the best for giving assurance in the seam integrity of any installed geomembrane. This method will detect leaks the others will not. This method should be the bottom line, the "last line of defense," test for any geomembrane usage where impermeability is critical. Often the labor intensity and time requirements of this method can be mitigated by using it in conjunction with the air lance method, conductivity method or an ultrasonic method. These latter three methods can locate larger anomalies rapidly. Thus the vacuum box will be left only small anomalies or pinholes to detect and its operation will be more continuous and thus less costly.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include leak detections, locations and markings. No example data sheet is provided.

Method No. 43

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Conductivity

Principle of Test Method: This method electrically inspects the continuity of a seam by detecting changes in conductivity.

Test Method

(1) Apparatus: Battery, battery charger, battery tester, ground cable, coil spring electrodes and power pack.

(2) Procedure: The inspection electrode is passed over the seam. When anomalies in the seam are detected an audible signal is actuated by the instrument. The method does not test seam strength.

(3) Reference: Copyright by Tinker & Rasor.

Limitations: This method was developed for high voltage electrical inspection of pipeline coatings. Changes in the sub-seam soil water content can cause a change in the soil's dielectric constant and affect the readings. Thus uniform sub-seam soil nature and water content are desirable for the conduct of this method.

Status of the Method: This method is applicable to a quality assurance program for a hazardous waste disposal disposal facility, for it will detect seam leaks as well as bubbles, thin spots or foreign particles. It is relatively inexpensive, and one man can operate it without special training. The high voltages involved should not present safety problems. Because of its wider use and acceptance this method was deemed to be currently more applicable for use at a hazardous waste disposal facility than the similar ultrasonic method.

Calibration Procedure: The instrument must be calibrated to the conductivity of the seam beforehand so that only anomalies are detected.

Documentation of Test: Items to be recorded include anomaly detections, locations and markings. No example data sheet is provided.

9 3 1 2 9 0 4 1 3 7 9

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Ultrasonic

Principle of Test Method: This method ultrasonically inspects the continuity of a seam by detecting anomalies in the ultrasound echo.

Test Method

(1) Apparatus: Krautkramer USM2/US K6 ultrasound device, transducer, battery.

(2) Procedure: The inspection beacon is passed over the seam. When anomalies are detected the feedback or ultrasound echo changes. The method does not test seam strength.

(3) Reference: Copyright by Schlegel Lining Technology, Inc.

Limitations: This method is only a rough locator of anomalies. It must be used in conjunction with the vacuum seam method in order to yield valid overall results.

Status of the Method: This method, when used as a preliminary to the vacuum seam method, locates larger anomalies, thus speeding up the subsequent use of the vacuum box and yielding overall quicker inspection times. However, it is less preferred than is the conductivity method, which performs the same function. The reason is that the conductivity method is equally rapid and slightly more accurate; i.e., it will locate more anomalies.

Calibration Procedure: The ultrasound device must be calibrated over a 10-mm linear base with a 46-decibel 100% echo.

Documentation of Test: Items to be recorded include anomaly detections, locations and markings. No example data sheet is provided.

APPENDIX H

WATERWAY AND OUTLET STRUCTURE DESIGN AND CONSTRUCTION

Presented in this Appendix are design procedures for waterways (see section 4.10.2.2) and outlet protection (see section 4.10.2.5). The source of much of this material is Appendix D of Lee et al. (1984).

H.1 Waterways

H.1.1 General Channel Design

The most commonly used formula for computing channel capacity is Manning's formula

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2}$$

where

- Q = discharge (cubic feet per second)
- n = coefficient of roughness
- A = cross-sectional area of the channel (square feet)
- R = hydraulic radius of the channel (feet; defined as the cross-sectional area divided by the wetted perimeter)
- S = longitudinal inclination of the channel (feet/feet)

The cross-sectional area and hydraulic radius for standard channel slopes are given in Table 4-43. Roughness coefficients for various channel linings are given in Table H-1.

Several examples are given below illustrating the use of Manning's formula for channel design. Data for solving these example problems are given in Figure H-1 and Tables H-2 through H-5.

The following example illustrates the use of Manning's formula for a lined trapezoidal channel.

9 3 1 2 9 0 4 1 3 8 1

TABLE H-1

ROUGHNESS COEFFICIENT (n) FOR VARIOUS CHANNEL LININGS
(Lee et al., 1984)

Channel lining	n value
Wood	
Planed, untreated	0.012
Planed, creosoted	0.012
Unplaned	0.013
Plank with battens	0.015
Lined with roofing paper	0.014
Concrete	
Trowel finish	0.013
Float finish	0.015
Finished, with gravel on bottom	0.017
Unfinished	0.017
Gunite, good section	0.019
Gunite, wavy section	0.022
On good excavated rock	0.020
On irregular excavated rock	0.027
Concrete bottom float finished with sides of:	
Dressed stone in mortar	0.017
Random stone in mortar	0.020
Cement rubble masonry, plastered	0.020
Cement rubble masonry	0.025
Dry rubble or riprap	0.030
Gravel bottom with sides of:	
Formed concrete	0.020
Random stone in mortar	0.023
Dry rubble or riprap	0.033
Brick	
Formed concrete	0.013
In cement mortar	0.015
Masonry	
Cemented rubble	0.025
Dry rubble	0.032
Dressed ashlar	0.015
Asphaltic concrete	
Machine finished	0.018
Hand finished	0.022
Natural channels not completely lined with vegetation	0.025
Gabion mattresses	0.028
Fabriform - Filter point (waffled surface)	0.025

FIGURE H-1

MANNING'S ROUGHNESS COEFFICIENT n RELATED TO VELOCITY TIMES HYDRAULIC RADIUS AND VEGETAL RETARDANCE (U.S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

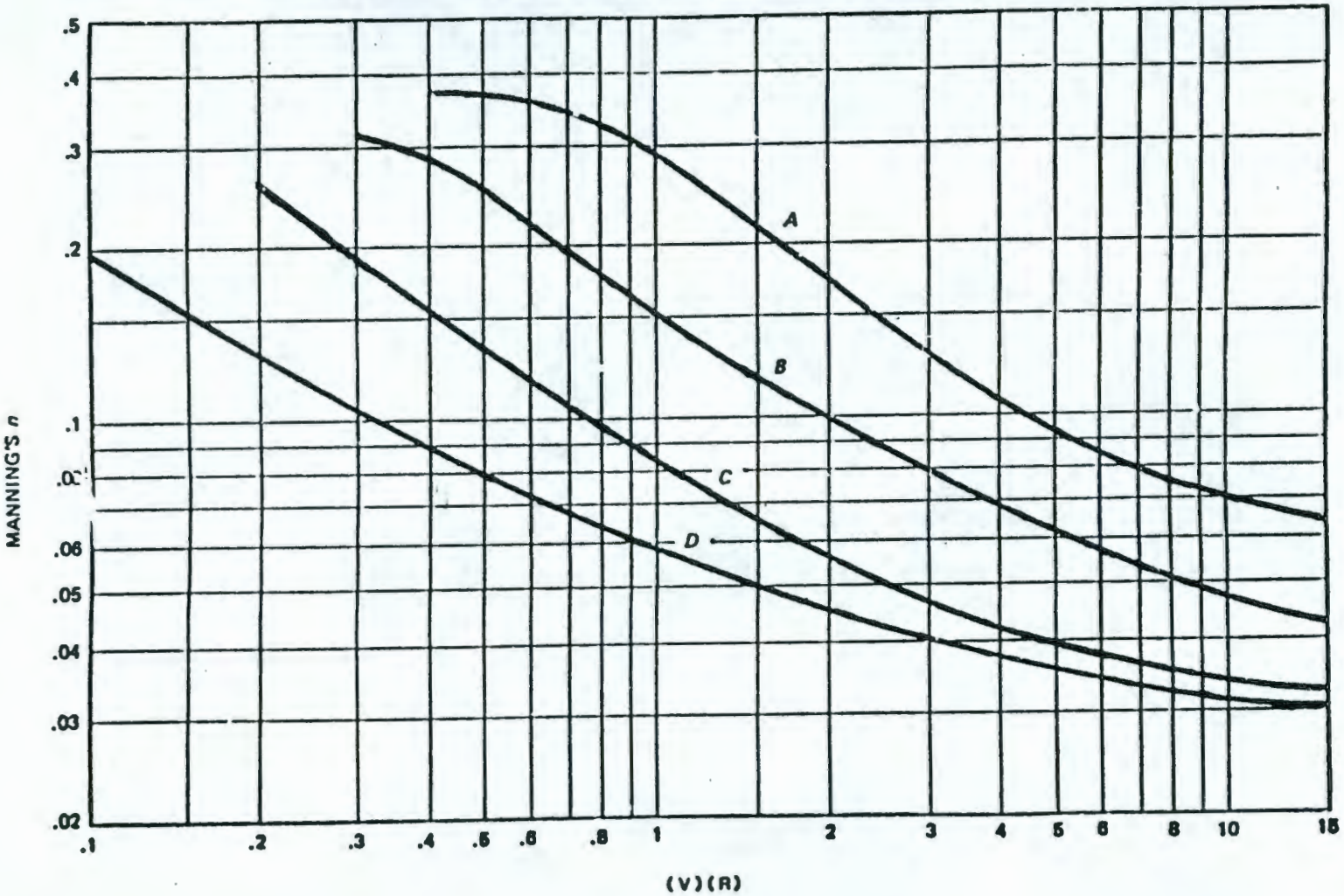

TABLE H-2

CLASSIFICATION OF VEGETAL COVER IN WATERWAYS BASED ON DEGREE OF FLOW RETARDANCE BY THE VEGETATION
(Mills and Clar, 1976)

Cover	Stand	Condition and Height	Retardance Curve[a]
Reed canarygrass	Excellent	Tall (average 36 in.)	A
Kentucky 31 tall fescue	Excellent	Tall (average 36 in.)	
Tufcote, Midland and Coastal bermudagrass	Good	Tall (average 12 in.)	B
Reed canarygrass	Good	Mowed (average 12 to 15 in.)	
Kentucky 31 tall fescue	Good	Unmowed (average 18 in.)	
Red fescue	Good	Unmowed (average 16 in.)	
Kentucky bluegrass	Good	Unmowed (average 16 in.)	
Redtop	Good	Average	
Kentucky bluegrass	Good	Headed (6 to 12 in.)	C
Red fescue	Good	Headed (6 to 12 in.)	
Tufcote, Midland and Coastal bermudagrass	Good	Mowed (average 6 in.)	
Redtop	Good	Headed (15 to 20 in.)	
Tufcote, Midland and Coastal bermudagrass	Good	Mowed (2-1/2 in.)	D
Red fescue	Good	Mowed (2-1/2 in.)	
Kentucky bluegrass	Good	Mowed (2 - 5 in.)	

[a]For retardance curves, see Figure 4-42.

TABLE H-3

PERMISSIBLE VELOCITIES FOR VEGETATED CHANNELS[a]

Cover	Permissible Velocity, fps					
	Erosion Resistant Soils (% Slope)			Easily Eroded Soils (% Slope)		
	0-5	5-10	Over 10	0-5	5-10	Over 10
Bermudagrass	8	7	6	6	5	4
Buffalo grass Kentucky bluegrass Smooth brome Blue grama Tall fescue Reed canarygrass	7	6	5	5	4	3
Lespedeza sericea Weeping lovegrass Alfalfa Crabgrass Redtop Red fescue	3.5	NR	NR	2.5	NR	NR
Grass mixture	5	4	NR	4	3	NR
Annuals for temporary protection	3.5	NR	NR	2.5	NR	NR

[a]Adapted from Haan and Barfield (1978) and Virginia Soil and Water Conservation Commission (1980), as presented in Lee et al. (1984).

NR = Not Recommended.

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TABLE H-4

PARABOLIC WATERWAY DESIGN FOR GRADE 5.0 PERCENT

V for Retardance D
T and D for Retardance C

Q cfs	V = 2.0		V = 2.5		V = 3.0		V = 3.5		V = 4.0		V = 4.5		V = 5.0		V = 5.5		V = 6.0	
	T	D	T	D	T	D	T	D	T	D	T	D	T	D	T	D	T	D
15	29	0.6	21	0.6	15	0.7	12	0.7	9	0.8	7	0.8	6	0.9	5	1.0		
20	39	0.6	28	0.6	20	0.7	16	0.7	12	0.8	10	0.8	8	0.9	6	1.0	5	1.1
25	49	0.6	35	0.6	25	0.7	20	0.7	15	0.8	12	0.8	10	0.9	8	1.0	7	1.0
30	58	0.6	42	0.6	30	0.7	24	0.7	18	0.8	14	0.8	11	0.9	9	1.0	8	1.0
35	68	0.6	49	0.6	35	0.7	28	0.7	21	0.8	17	0.8	13	0.9	11	0.9	9	1.0
40	77	0.6	56	0.6	40	0.7	32	0.7	24	0.8	19	0.8	15	0.9	12	0.9	10	1.0
45	86	0.6	63	0.6	44	0.7	36	0.7	27	0.8	21	0.8	17	0.9	14	0.9	12	1.0
50	96	0.6	69	0.6	49	0.7	40	0.7	30	0.8	24	0.8	19	0.9	15	0.9	13	1.0
55	105	0.6	76	0.6	54	0.7	44	0.7	33	0.8	26	0.8	21	0.9	17	0.9	14	1.0
60	114	0.6	83	0.6	59	0.7	48	0.7	36	0.8	28	0.8	22	0.9	18	0.9	15	1.0
65	123	0.6	89	0.6	63	0.7	52	0.7	38	0.8	31	0.8	24	0.9	19	0.9	17	1.0
70	132	0.6	96	0.6	68	0.7	56	0.7	41	0.8	33	0.8	26	0.9	21	0.9	18	1.0
75	142	0.6	102	0.6	73	0.7	59	0.7	44	0.8	35	0.8	28	0.9	22	0.9	19	1.0
80	151	0.6	109	0.6	78	0.7	63	0.7	47	0.8	37	0.8	30	0.9	24	0.9	20	1.0
90	169	0.6	122	0.6	87	0.7	71	0.7	53	0.8	42	0.8	33	0.9	27	0.9	23	1.0
100	187	0.6	136	0.6	97	0.7	79	0.7	59	0.8	47	0.8	37	0.9	30	0.9	26	1.0
110	205	0.6	149	0.6	106	0.7	86	0.7	64	0.8	51	0.8	41	0.9	33	0.9	28	1.0
120	223	0.6	162	0.6	115	0.7	94	0.7	70	0.8	56	0.8	44	0.9	35	0.9	31	1.0
130	241	0.6	175	0.6	125	0.7	102	0.7	76	0.8	60	0.8	48	0.9	38	0.9	33	1.0
140	259	0.6	188	0.6	134	0.7	109	0.7	81	0.8	65	0.8	52	0.9	41	0.9	36	1.0
150	276	0.6	201	0.6	143	0.7	117	0.7	87	0.8	69	0.8	55	0.9	44	0.9	38	1.0
160	294	0.6	213	0.6	152	0.7	124	0.7	93	0.8	74	0.8	59	0.9	47	0.9	40	1.0
170	311	0.6	226	0.6	162	0.7	132	0.7	98	0.8	78	0.8	62	0.9	50	0.9	43	1.0
180	329	0.6	239	0.6	171	0.7	139	0.7	104	0.8	83	0.8	66	0.9	53	0.9	45	1.0

Q = Flow in cubic feet per second, V = Velocity in feet per second, T = Top width in feet, D = Depth in feet

TABLE H-5

TRAPEZOIDAL CHANNEL DESIGN FOR GRADE 2.0 PERCENT
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

C Retardance Side Slope = 2:1

Q cfs	b = 2		b = 4		b = 6		b = 8		b = 10		b = 12		b = 14		b = 16	
	D	V	D	V	D	V	D	V	D	V	D	V	D	V	D	V
15	1.2	3.0	0.9	2.7	0.8	2.4	0.7	2.1	0.7	1.9	0.7	1.7	0.6	1.6	0.6	1.4
20	1.3	3.4	1.0	3.2	0.9	2.9	0.8	2.6	0.7	2.3	0.7	2.1	0.7	1.0	0.6	1.8
25	1.4	3.8	1.1	3.6	1.0	3.3	0.9	3.0	0.8	2.7	0.7	2.5	0.7	2.3	0.7	2.1
30	1.5	4.2	1.2	3.9	1.0	3.6	0.9	3.3	0.8	3.1	0.8	2.8	0.7	2.6	0.7	2.4
35	1.6	4.4	1.3	4.2	1.1	3.9	1.0	3.6	0.9	3.3	0.8	3.1	0.8	2.9	0.7	2.7
40	1.6	4.7	1.3	4.5	1.1	4.2	1.0	3.9	0.9	3.6	0.9	3.4	0.8	3.1	0.8	2.9
45	1.7	4.9	1.4	4.7	1.2	4.5	1.1	4.2	1.0	3.9	0.9	3.6	0.8	3.4	0.8	3.2
50	1.8	5.2	1.5	5.0	1.2	4.7	1.1	4.4	1.0	4.1	0.9	3.9	0.9	3.6	0.8	3.4
55	1.9	5.4	1.5	5.1	1.3	4.9	1.2	4.6	1.0	4.3	1.0	4.0	0.9	3.8	0.9	3.6
60	1.9	5.5	1.6	5.3	1.4	5.1	1.2	4.8	1.1	4.5	1.0	4.2	0.9	4.0	0.9	3.8
65	1.9	5.7	1.6	5.5	1.4	5.3	1.2	5.0	1.1	4.7	1.0	4.4	1.0	4.2	0.9	4.0
70	2.0	5.9	1.7	5.7	1.4	5.5	1.3	5.2	1.2	4.9	1.1	4.6	1.0	4.3	1.0	4.1
75			1.7	5.9	1.5	5.6	1.3	5.3	1.2	5.0	1.1	4.7	1.0	4.5	1.0	4.3
80					1.5	5.8	1.4	5.5	1.2	5.2	1.1	4.9	1.1	4.7	1.0	4.4
90							1.4	5.8	1.3	5.5	1.2	5.2	1.1	5.0	1.1	4.7
100									1.4	5.8	1.3	5.5	1.2	5.2	1.1	5.0
110									1.4	6.0	1.3	5.8	1.2	5.5	1.1	5.2
120											1.4	6.0	1.3	5.7	1.2	5.4
130													1.3	5.9	1.2	5.7
140															1.3	5.9

Q = Flow, cubic feet per second, V = Velocity, feet per second, b = Bottom width, feet, D = Depth, feet.

Problem: Given a concrete (trowal finish) lined trapezoidal channel where space limitations dictate a maximum top width (T) of 10 ft, a depth (y) of 2 ft, and a side slope of 2H:1V (due to foundation considerations); determine the channel cross-section and longitudinal inclination (S) that will carry a flow of 200 cubic feet per second (cfs).

Solution: Using the formula in Table 4-43, the following geometric properties can be obtained:

a. Bottom width (b),
Since
$$T = b + 2\,z\,y\ ,$$
it follows that
$$b = T - 2\,z\,y$$
$$b = 10 - 2\,(2)(2)$$
$$b = 2\ \text{ft}$$

b. Area (A),
$$A = (b + z\,y)\,y$$
$$A = (2 + (2)(2))\ 2$$
$$A = 12\ \text{ft}^2$$

c. Hydraulic Radius (R),

$$R = \frac{(b + zy)\ y}{b + 2y\ \sqrt{1 = z^2}}$$

$$R = \frac{(2 + (2)(2))\ 2}{2 + 2(2)\ \sqrt{1 + (2)^2}}$$

$$R = 1.10\ \text{ft}$$

The values for Q , A , and R , along with a Manning's "n" value of 0.013 (from Table H-1) are inserted into Manning's formula

$$Q = \frac{1.49}{n}\ A\ \ R^{2/3}\ \ S^{1/2}$$

$$200\ \text{cfs} = \frac{1.49}{0.013}\ (12\ \text{ft}^2)\ (1.10\ \text{ft}^{2/3})\ \ S^{1/2}$$

therefore,

$$S = 0.019 = 1.9\ \text{pct; say 2 pct}$$

Methods of optimizing the channel's longitudinal inclination (S) and depth are presented in detail in Chow (1959).

The design of a grass-lined channel is influenced by the following factors.

- Type of vegetative cover
- Condition of vegetation (retardance factor)
- Permissible velocity based on vegetative cover
- Capacity of channel
- Longitudinal inclination (slope)
- Channel cross section

Often, waterway design tables are available for different channel cross sections and slopes, as illustrated in the following example problems taken from Lee et al. (1984).

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Problem 1

Determine the nonerosive velocity and dimensions for stability and capacity for a waterway with parabolic cross section.

Given:	Runoff	Q = 55 cfs
	Grade	= 5.1 percent
	Vegetative cover	= Kentucky bluegrass
	Condition of vegetation	
	Good stand-mowed (3 in. - 4 in.)	= D-curve retardance (see Table H-2)
	Good stand-headed (6 in. - 12 in.)	= C-curve retardance (see Table H-2)
	Permissible velocity	= 4 ft/sec (see Table H-3)

Solution: Use the Parabolic Waterway Design Table for the grade nearest 5.1 percent (grade 5.0% - Table H-4). Horizontally opposite 55 cfs and under the columns headed V = 4.0 ft/sec, find T = 33 ft, and D = 0.8 ft.

Therefore, a waterway with parabolic cross section, a top width of 33 ft, and a depth of 0.8 ft will carry 55 cfs at a maximum velocity of 4 ft per second when the vegetative lining is short (3 in. to 4 in. in height). This complies with the requirement for nonerosive velocity when vegetation is short (D retardance) and for capacity when vegetation is tall (C retardance).

Problem 2

Determine the nonerosive velocity and dimensions for a waterway with trapezoidal cross section.

Given:	Runoff	Q = 55 cfs
	Grade	= 2.0 percent
	Side slopes	= 2:1
	Vegetative cover	= Kentucky bluegrass
	Condition of vegetation	
	Good stand - headed (6 in. - 12. in.)	= C-curve retardance (see Table H-2)
	Permissible velocity	= 5 ft/sec (see Table H-3)

Solution: Use the Trapezoidal Channel Design Table for the Grade 2.0 percent (Table H-5). Horizontally opposite 55 cfs and under the column headed b = 6 ft, find D = 1.3 ft, and V = 4.9 ft/second.

Therefore, a waterway with trapezoidal cross section, 2:1 side slope, bottom width of 6 ft, and a depth of 1.3 ft will carry 55 cfs at a maximum velocity of 4.9 ft per second for C-curve retardance.

The following problem illustrates a method of determining the safe velocity for a trapezoidal channel without the advantages of a design table like Table H-5.

Problem 3

(Clar et al. 1983)

Given:	Runoff	Q = 55 cfs
	Grade	= 3.0 percent
	Side slopes	= 3:1
	Vegetative cover	= Kentucky bluegrass
	Condition of vegetation	
	Good stand - mowed (3 in. - 4 in.)	= D-curve retardance (see Table H-2)
	Good stand - headed (6 in. - 12 in.)	= C-curve retardance (see Table H-2)
	Permissible velocity	= 5 ft/sec (see Table H-3)

Solution: The solution is a trial-and-error process. The first step is to design for stability when the vegetation is short (D retardance), and the second step is to design for capacity when the vegetation is tall (C retardance).

Step 1 - Stability - D-curve retardance

$$Q = 55 \text{ cfs}$$

$$V_{max} = 5 \text{ ft/sec}$$

$$A = \frac{Q}{V_{max}} = \frac{55}{5} = 11 \text{ ft}^2$$

Try Bottom Width (b) = 12 ft

$$A = bD + zD^2$$

$$11 = 12D + 3D^2$$

Solve for D by use of the quadratic equation.

$$ax^2 + bx + c = 0$$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$D = \frac{-12 \pm \sqrt{12^2 - 4(3)(-11)}}{2(3)}$$

$$= \frac{-12 + 16.61}{6} = \frac{4.61}{6}$$

$$= 0.77 \text{ ft}$$

Hydraulic Radius

$$R = \frac{\text{area (A)}}{\text{wetted perimeter (P)}} = \frac{bd + zD^2}{b + 2D\sqrt{z^2 + 1}}$$

$$R = \frac{12\,(0.77) + 3\,(0.77^2)}{12 + 2(0.77)\sqrt{3^2 + 1}}$$

9 1 1 2 9 0 4 1 3 9 1

$$R = \frac{9.24 + 1.78}{12 + 4.87}$$

$$R = \frac{11.02}{16.87} = 0.65$$

$$V(R) = 5(0.65) = 3.25$$

From Figure H-1 for VR = 3.25 and D retardance, n = 0.04

$$V = \frac{1.49}{n} R^{2/3} \; S^{1/2} \quad \text{(Manning's equation)}$$

where n is the roughness coefficient, R is the hydraulic radius, and S is the hydraulic gradient.

$$V = \frac{1.49}{0.04} (0.65^{2/3}) (0.03^{1/2}) = 4.83 \text{ ft/sec}$$

This is acceptable, but is less than V_{max}. Therefore, try a slightly smaller channel.

Bottom width = 10 ft
$11 = 10D + 3D^2$
D = 0.87 ft
R = 0.71
VR = 3.55
n = 0.04 (see Figure H-1)

$$v = \frac{1.49}{n} R^{2/3} \; S^{1/2} = 5.15 \text{ which is greater than } V_{max}$$

Therefore, select design bottom width = 12 ft

Velocity = 4.83 ft/sec for D retardance
Depth = 0.8 ft

Step 2 - Capacity (C retardance)

Determine additional depth needed to offset the increased retardance and decrease velocity.

Try D = 0.9 ft

$$A = (12)(0.9) + 3(0.9^2) = 13.23$$

$$R = \frac{A}{P} = \frac{13.23}{12 + 2(0.9)\sqrt{3^2 + 1}} = 0.75$$

Assume $V = 4.4$ ft/sec

$$VR = (4.4)(0.75) = 3.30$$

For $VR = 3.30$ and C retardance, $n = 0.046$ (Figure H-1)

$$V = \frac{1.49}{0.046}(0.75^{2/3})(0.03^{1/2}) = 4.62 \text{ ft/sec}$$

Since 4.62 ft/sec is greater than the assumed V, assume $V = 4.6$ ft/sec

$$VR = (4.6)(0.75) = 3.45$$

$n = 0.046$ (Figure H-1)

$$V = \frac{1.49}{0.046}(0.75^{2/3})(.03^{1/2}) = 4.62 \text{ ft/sec}$$

This is close enough.

Therefore, dimensions and velocities are as follows:

Bottom width = 12 ft
Side slopes = 3H:1V

For D retardance - V = 4.83 ft/sec
D = 0.8 ft
For C retardance - V = 4.62 ft/sec
D = 0.9 ft

H.1.2 Riprap-lined channels

The design of a channel using riprap as a lining differs little from that for asphalt or concrete. One difference, however, is that no single number for Manning's roughness coefficient (n) exists. Manning's n is obtained by estimating a median riprap size (d_{50}) and then getting the corresponding n value from Figure H-2. Another difference lies in that the riprap alone may not restrict the movement of soil through the riprap. Soil escaping from underneath the riprap could lead to serious undermining of the channel slope. This erosion would effectively defeat the purpose of the riprap. In this case, a filter blanket consisting of a graded, granular mixture or a geotextile would be required between the riprap and the underlying soil surface. General design criteria for riprap linings are presented in Table H-6. Table H-7 contains guidance to be considered when writing construction specifications.

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FIGURE H-2

MANNING'S ROUGHNESS COEFFICIENT n FOR RIPRAP-LINED CHANNELS

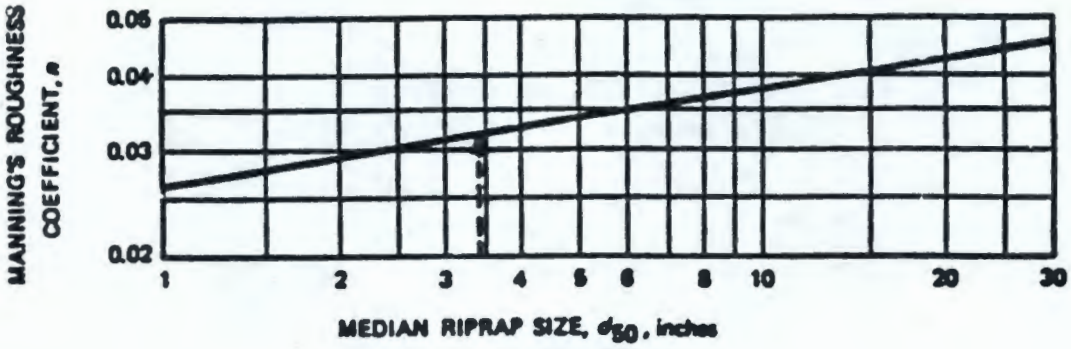


TABLE H-6

GENERAL DESIGN CRITERIA FOR RIPRAP-LINED CHANNELS

a. Well-graded riprap is preferred to a uniform or gap-graded mixture.

b. The design stone size is the d_{50} (median stone diameter). The d_{50} is the stone size which is exceeded in weight by 50 percent of the mixture.

c. Riprap sizes for both channel bends and straight portions of the channels must be calculated.

d. If the d_{50} of the riprap computed for the bends is less than 10 percent greater than the d_{50} of the riprap for the straight channels, then the straight channel riprap can be used through the bend.

e. The diameter of the largest stone should be twice the d_{50} size.

f. Riprap lined slopes are usually 2H:1V.

TABLE H-7

CONSTRUCTION SPECIFICATION GUIDANCE FOR CHANNEL RIPRAP

a. Riprap sizes are designated by either diameter or the weight of the stones. See Table 4-51.

b. Riprap shall consist of rough unhewn quarry stone or field stone. The stone should be hard, angular, and not disintegrate upon exposure to water or weathering. The specific gravity of the individual stones should be at least 2.5.

c. The riprap determined to be stable under the flow conditions shall be considered the minimum size. Riprap gradations in the area shall equal or exceed the minimum size.

d. The minimum thickness of a riprap layer should be twice the maximum stone diameter but not less than 6 inches.

e. The riprap should extend up the banks to a height above the maximum depth of flow or to a point where vegetation can adequately protect the channel.

f. The riprap size used in a bend should extend upstream from the point of curvature and downstream from the point of tangency a distance equal to five times the channel's bottom width (Figure 4-44). The riprap should be placed across the channel's full cross section.

g. Where the bottom of the channel is not to be lined with riprap, the toe of the slope riprap should extend at least 1.5 times the maximum stone size below the channel bottom, but not less than 1 foot.

Examples of stone size specifications are given in Table H-8. Table H-9 presents general design criteria for filter blankets. Figure H-3 shows factors influencing riprap at channel bends. Figures H-4 and H-5 give information on channel cross-section and stone size, respectively, for trapezoidal channels. Various other design information is presented in Figures H-6 through H-8.

The requirement that riprap stones be angular is flexible. The stones used in the extensive tests of Anderson, Paintal, and Davenport (1970) varied from angular to fairly rounded. If, for example, a local supply of cobble gravel is available which meets size and durability criteria, the gravel may be acceptable riprap.

TABLE H-8

RIPRAP DESIGNATION EXAMPLES

a. Riprap Designation Based Primarily on Weight

Weight (lbs)[a]	Mean Spherical Diameter (ft)	Rectangular Shape	
		Length (ft)	Width, Height (ft)
50	0.8	1.4	0.5
100	1.1	1.75	0.6
150	1.3	2.0	0.67
300	1.6	2.6	0.9
500	1.9	3.0	1.0
1,000	2.2	3.7	1.25
1,500	2.6	4.7	1.5
2,000	2.75	5.4	1.8
4,000	3.6	6.0	2.0
6,000	4.0	6.9	2.3
8,000	4.5	7.6	2.5
20,000	6.1	10.0	3.3

b. Riprap Designation Based Primarily on Diameter[b]

Riprap Class	D_{15} Weighted (lbs)[a]	Mean D_{15} Spherical Diameter (ft)	Mean D_{50} Spherical Diameter (ft)
Class I	50	0.8	1.1
Class II	150	1.3	1.6
Class III	500	1.9	2.2
Type I	1,500	2.6	2.8
Type II	6,000	4.0	4.5

[a]Based on 165 pcf.

[b]From Virginia Department of Highways and Transportation; as cited in Lee et al. (1984)

TABLE H-9

DESIGN CRITERIA FOR FILTER BLANKETS

a. A filter blanket is required where:

1. The riprap is not well graded down to the 1-inch size aggregate.

2. The slope underlying the riprap on a slope is sand-size or smaller with a plasticity index less than 10. This also applies to lenses or layers in the slope that are thicker than 3 inches.

b. The following relationships should exist for a graded gravel filter:

1. $\frac{d_{15} \text{ of filter material}}{d_{85} \text{ of protected soil}} \leq 5$

2. $\frac{d_{50} \text{ of filter material}}{d_{50} \text{ of protected soil}} \leq 25$

3. $20 \geq \frac{d_{15} \text{ of filter material}}{d_{15} \text{ of protected soil}} > 5$

c. The following relationships should exist for a filter cloth (geotextile):

1. For filter cloth adjacent to granular materials containing 50 percent or less (by weight), of fine particles (less than 0.074 mm):

$$\frac{d_{85} \text{ base (mm)}}{\text{EOS}^a \text{ filter cloth (mm)}} > 1$$

2. Total open area of filter is less than 36 percent.

3. For filter cloth adjacent to all other soils: EOS less than U. S. Standard Sieve No. 70.

4. Total open area of filter is less than 10 percent.

5. No filter cloth should be used with less than 4 percent open area or an EOS less than U. S. Standard Sieve No. 100.

6. A minimum of 4 inches of gravel or sand should be placed on a filter cloth on which riprap (12 inches or larger) is to be laid.

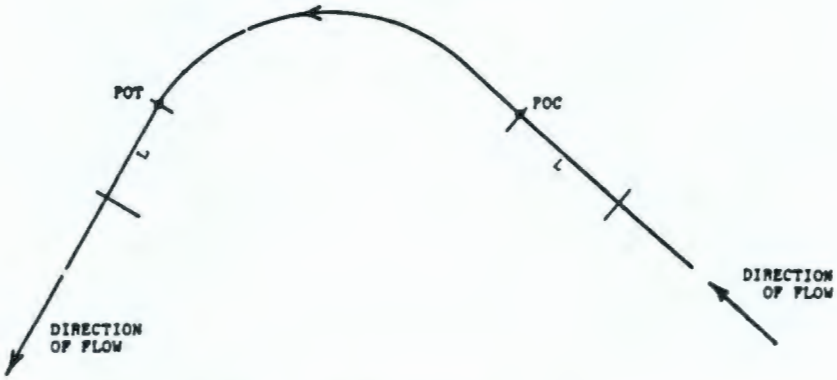
7. Side slopes should be 2H:1V or flatter to prevent gravel buffer from sliding down filter cloth.

[a]EOS = equivalent opening size to a U. S. standard sieve size.

9 3 1 2 9 0 4 1 3 9 7

FIGURE H-3

RIPRAP AT BENDS



POC = POINT OF CURVATURE

POT = POINT OF TANGENCY

L = 5 TIMES BOTTOM WIDTH OF CHANNEL

FIGURE H-4

P/r RATIO FOR TRAPEZOIDAL CHANNELS (U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

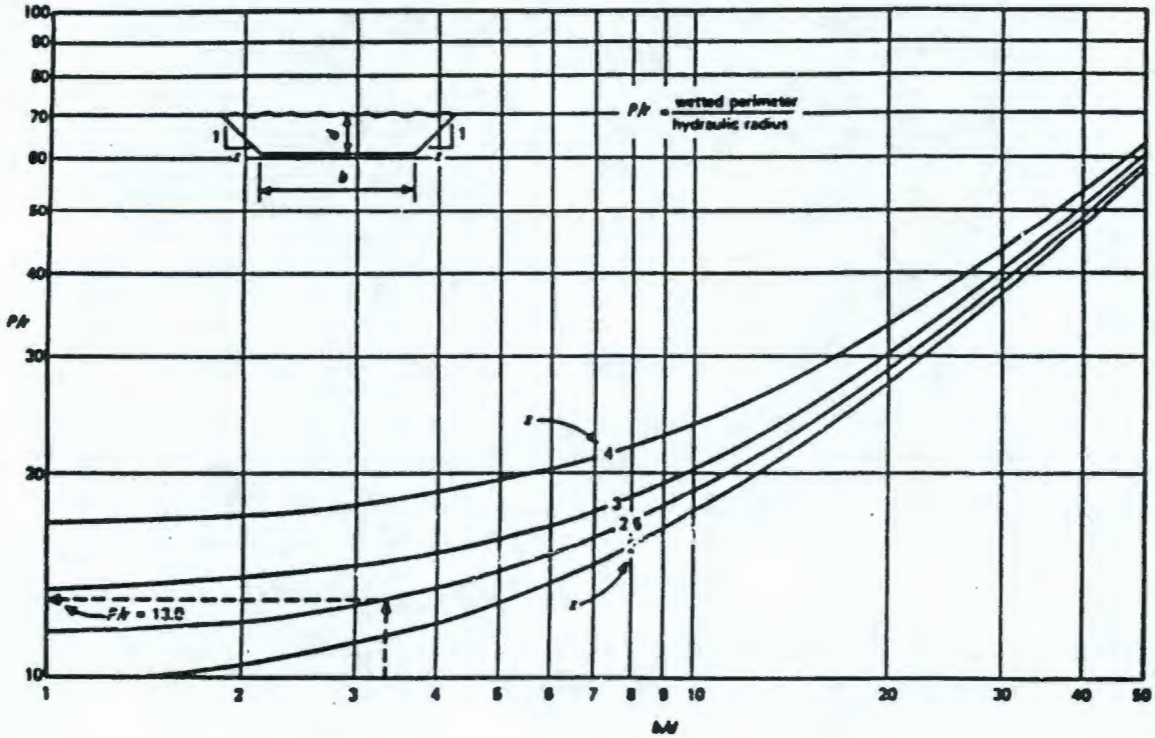


FIGURE H-5

MEDIAN RIPRAP DIAMETER FOR STRAIGHT TRAPEZOIDAL CHANNELS
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

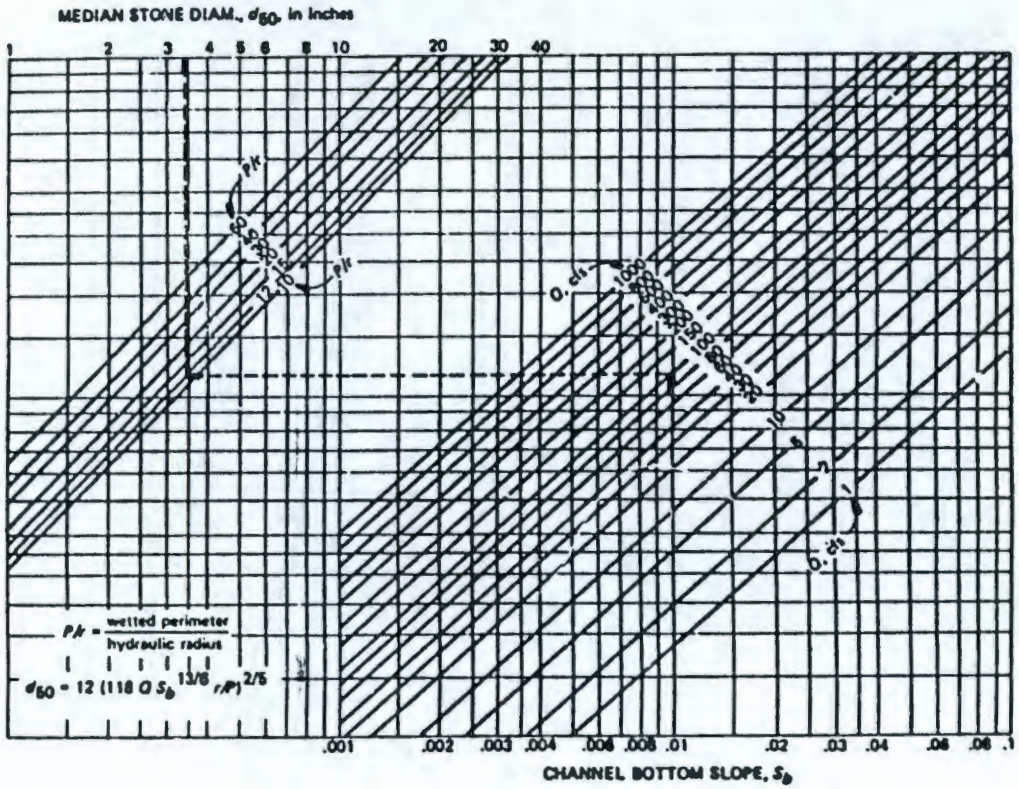


FIGURE H-6

RIPRAP SIZE CORRECTION FACTOR FOR FLOW IN CHANNEL BENDS
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

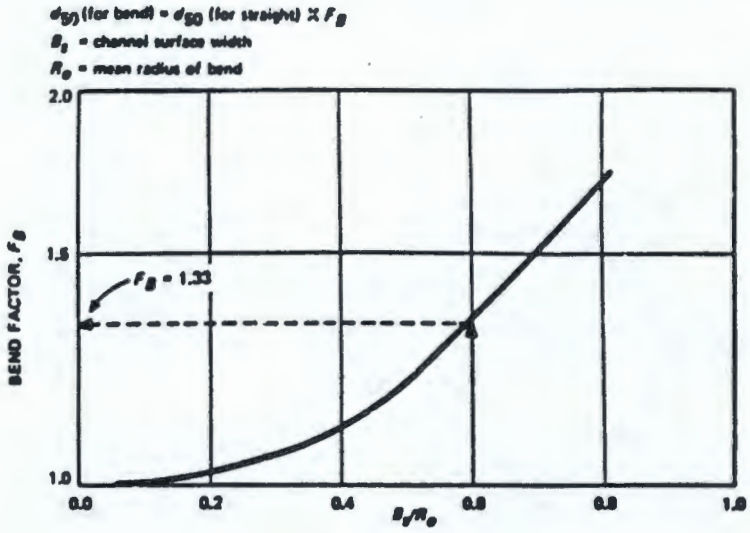


FIGURE H-7

MAXIMUM RIPRAP SIDE SLOPE WITH RESPECT TO RIPRAP SIZE
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)

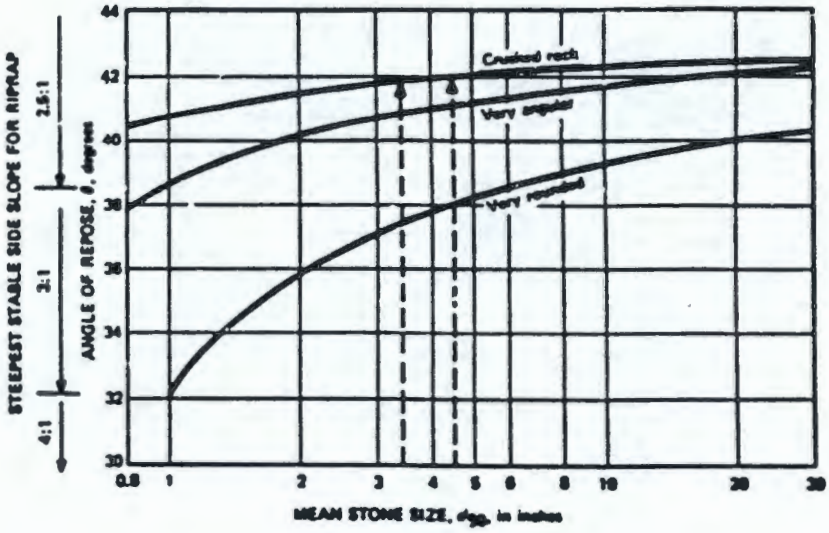
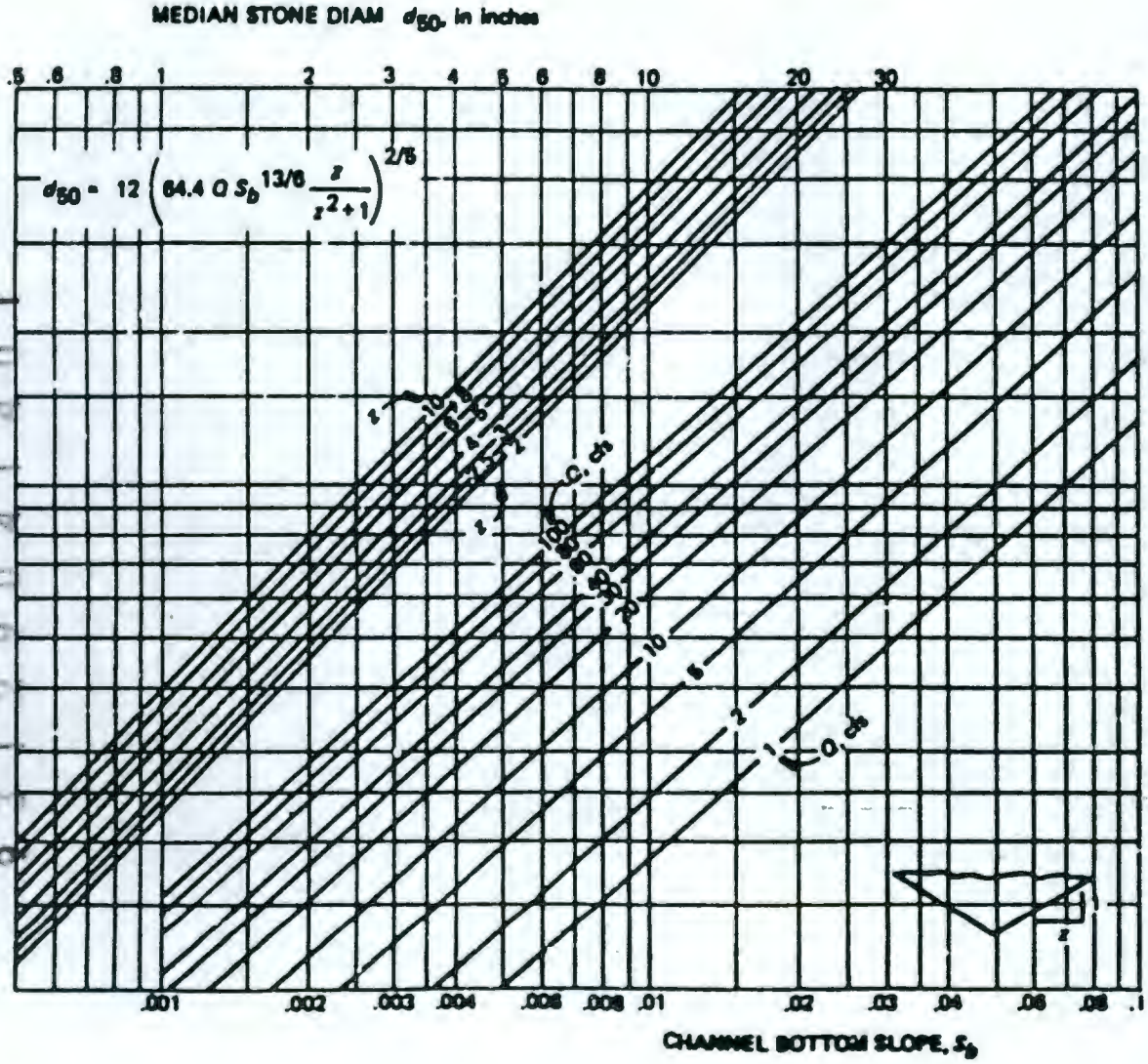


FIGURE H-8

MEDIAN RIPRAP DIAMETER FOR STRAIGHT TRIANGULAR CHANNELS
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1976)



The following examples, taken from Lee et al. (1984), illustrate riprap lining designs based on the assumption that the channel dimensions and slope have already been determined.

For a <u>trapezoidal</u> riprap-lined channel:

a. Calculate the b/d ratio and find the P/r ratio on Figure H-4.

b. From Figure H-5, using S_b , Q , and P/r , find the median riprap diameter, d_{50} , for straight channels.

c. On Figure H-2, find the actual n value corresponding to the d_{50} from step 2. If the estimated and actual n values are not in reasonable agreement, another trial must be made.

d. For channels with bends, calculate the ratio B_s/R_o , where B_s is the channel surface width and R_o is the radius of the bend. Use Figure H-6 to find the bend factor, F_B . Multiply the d_{50} for straight channels by the bend factor to determine riprap size to be used in bends. Riprap must extend across the full channel section and must extend upstream and downstream from the ends of the curve a distance equal to five times the bottom width.

e. From Figure H-7, determine the maximum stable side slope of riprap surface.

f. Determine the safety factor of the design and insure that it is greater than 1. This is given by:

$$SF = \frac{\text{Cos } r \text{ Tan } d}{n' \text{ Tan } d + \text{Sin } R \text{ cos } b}$$

where:

R is the side slope angle
d is the angle of repose
b is the angle indicating particle movement
n' is the stability number for particles on embankment side slopes
n' is given by:

$$n' = n \left[\frac{1 + \text{Sin } (S + B)}{2} \right]$$

where:

S is the dip angle of the channel
n is the stability number for particles on plane surfaces
n is given by:

$$n = \frac{0.30\ V^2}{(S_s - 1)gK}$$

where:

V is the velocity of flow in the channel
S_s is the specific gravity of the individual stones
g is the acceleration of gravity
K is the size of the riprap stone
b is given by:

$$b = \mathrm{Tan}^{-1}\left(\frac{\mathrm{Cos}\ S}{\frac{2\ \mathrm{Sin}\ R}{n\ \mathrm{Tan}\ d} + \mathrm{Sin}\ S}\right)$$

Triangular riprap-lined channel:

a. From Figure H-8, using Sb , Q , and z , find the median riprap diameter, d_{50} , for straight channels.

b. From Figure H-2, find the actual n value. If the estimated and actual n value are not in reasonable agreement, another trial must be made.

c. For channels with bends, see step four under Trapezoidal Channels.

d. For safety-factor calculation, see Trapezoidal Channels.

The riprap size to be specified on the plans is the maximum stone size in the mixture which is 2.0 times the d_{50} . The thickness of the riprap layer is 2.0 times the maximum stone size, but not less than 6 in. Freeboard is added to the channel depth and should not be less than 0.2 times the depth of flow, or 0.3 ft, whichever is greater.

Example:

Given:

Trapezoidal channel:
Q = 100 cfs
S = 0.01 ft/ft
Side slopes 2.5.1, 0 = 22°
Mean bend radius, R = 25 ft
n = 0.033 (estimated and used to design the channel to find that b = 6 ft and d = 1.8 ft)
Type of rock available is crushed stone.

Solution:

Straight channel reach

$b/d = 6/1.8 = 3.3$

From Figure H-4, $P/r = 13.0$

From Figure H-5, $d_{50} = 3.4$ inch

From Figure H-2, n (actual) = 0.032, which is reasonably close to the estimated n of 0.033

Maximum riprap size = 2.0 x 3.4 = 6.8 in.

Riprap thickness = 2.0 x 5.1 = 10.2 in.

Use 7 in. as maximum riprap size and 10 in. as riprap layer thickness

Channel bend

$B_s = b + 2zd = 6 + (2)(2.5)(1.8) = 15$ ft

$B_s/R_o = 15/25 = 0.60$

From Figure H-6, F = 1.33

F = 1.33 J 1.1; therefore, the bend factor must be used.

Riprap size in bend, $d_{50} = 3.4 \times 1.33 = 4.52$ in.

Maximum riprap size in bend = 4.52 x 2.0 = 9.04 in.

Riprap thickness = 6.78 x 2.0 = 13.56 in.

Use 9 in. for maximum riprap size and 14 in. for riprap layer thickness

The heavier riprap for the bend shall extend upstream and downstream from the ends of the bend a distance of (5)(6) = 30 ft

The riprap for $d_{50} = 3.4$ inch and 4.52 inch, which will both be stable on a 2.5:1 side slope (Figure H-7)

Freeboard = (0.2)(1.8) = 0.36 ft which is not less than 0.3 ft

Therefore, minimum freeboard is 0.36 ft. Use 0.4 ft.

Safety factor

Area of Channel = 1/2 (b+w)d

$w = b+2\ (1.8/\text{Tan } 22^\circ) = 15$ ft

$A = 1/2\ (6+15)1.8 = 18.8\ ft^2$

$V = Q/A = 100\ cfs/18.8 = 5.31$ ft/S

$$n = \frac{0.3\ (5.31)^2}{(2.65 - 1)(32.2)(0.58\ ft)} = 2.75$$

$$b = \text{TAN}^{-1}\left[\frac{\text{Cos } 1^\circ}{\dfrac{2 \text{ Sin } 22.}{0.275\ (\text{Tan } 35^\circ)} + \text{Sin } 1^\circ}\right] = 14.3$$

$$n' = 0.275\ \frac{[1 + \text{SIN } (1 + 14.3)]}{2} = 0.174$$

$$SF = \frac{\text{Cos } 22 \text{ Tan } 35}{0.174\ (\text{Tan } 35) + \text{Sin } 22 \text{ Cos } 14.3} = 1.34$$

H.2 Outlet Protection

H.2.1 General

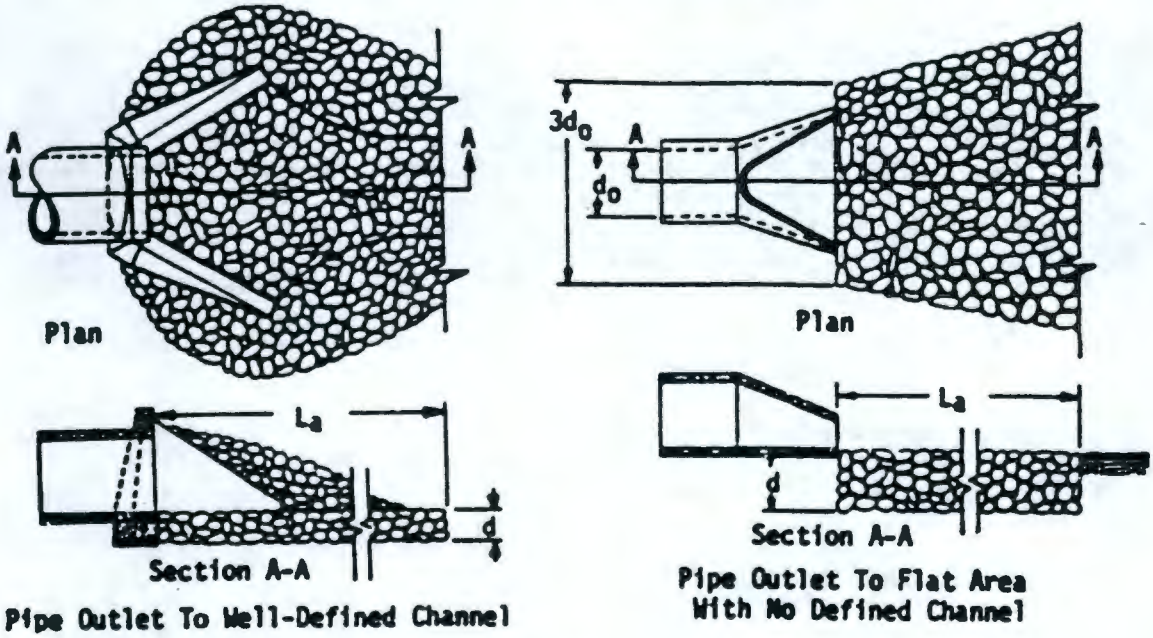
Outlet protection is the providing of energy dissipation devices and erosion-resistant channel sections between drainage outlets and stable existing downstream channels. The channel sections may be rock-lined, vegetated, paved with concrete, or otherwise made erosion resistant. The purpose of outlet protection is to prevent scour around pipe outlets.

The most commonly used device for outlet protection is a structurally lined apron. These aprons are generally lined with riprap, grouted riprap, or concrete. They are constructed at a zero grade for a distance which is related to the outlet flow rate and the tailwater level.

This practice applies to storm drain outlets, road culverts, paved channel outlets, etc., where a large erosion potential exists. Analysis and appropriate treatment should be provided along the entire length of the flow path from the end of the conduit, channel, or structure to the point of entry into

FIGURE H-9

PIPE OUTLET CONDITIONS
(VIRGINIA SOIL AND WATER CONSERVATION COMMISSION, 1980)



d = 2.0 times the maximum stone diameter but not less than 6 inches.

9 3 1 2 9 0 4 1 4 0 5

an existing stream or publicly maintained drainage system. This is especially important if the velocity of flow at the design capacity of the outlet will exceed the permissible velocity of the receiving channel or area.

Stormwater which is transported through man-made conveyance systems at design capacity generally reaches a velocity which exceeds the limiting velocity of the receiving channel. This may result in scour of the stormwater outlet. To prevent scour, a flow transition structure is needed which will absorb the initial impact of the flow and reduce the flow velocity to a level which will not erode the receiving channel or area.

H.2.2 Pipe Outlets

Each pipe outlet should have a structurally lined apron or other suitable energy dissipating structure immediately downstream from the outlet (see Figure H-9). The structurally lined apron should meet the following criteria:

a. Tailwater depth. The depth of tailwater immediately below the pipe outlet must be determined for the design capacity of the pipe. Manning's equation may be used to determine tailwater depth. A minimum tailwater condition is achieved when the tailwater depth is less than half the diameter of the outlet pipe. A maximum tailwater condition is achieved when the tailwater depth is greater than half the pipe diameter. Pipes which outlet onto flat areas with no defined channel are assumed to have a minimum tailwater condition.

b. Apron length. The apron length is deter[illegible] by the tailwater condition using the curves shown in Figures H-10 and H-11.

c. Apron width. When the pipe discharges directly into a well-defined channel, the apron should extend across the channel bottom and up the channel banks to an elevation one foot above the maximum tailwater depth or to the top of the bank (whichever is less), but no lower than two-thirds of the vertical conduit dimension above the conduit invert. If the pipe discharges onto a float area with no defined channel, the width of the apron is determined as follows:

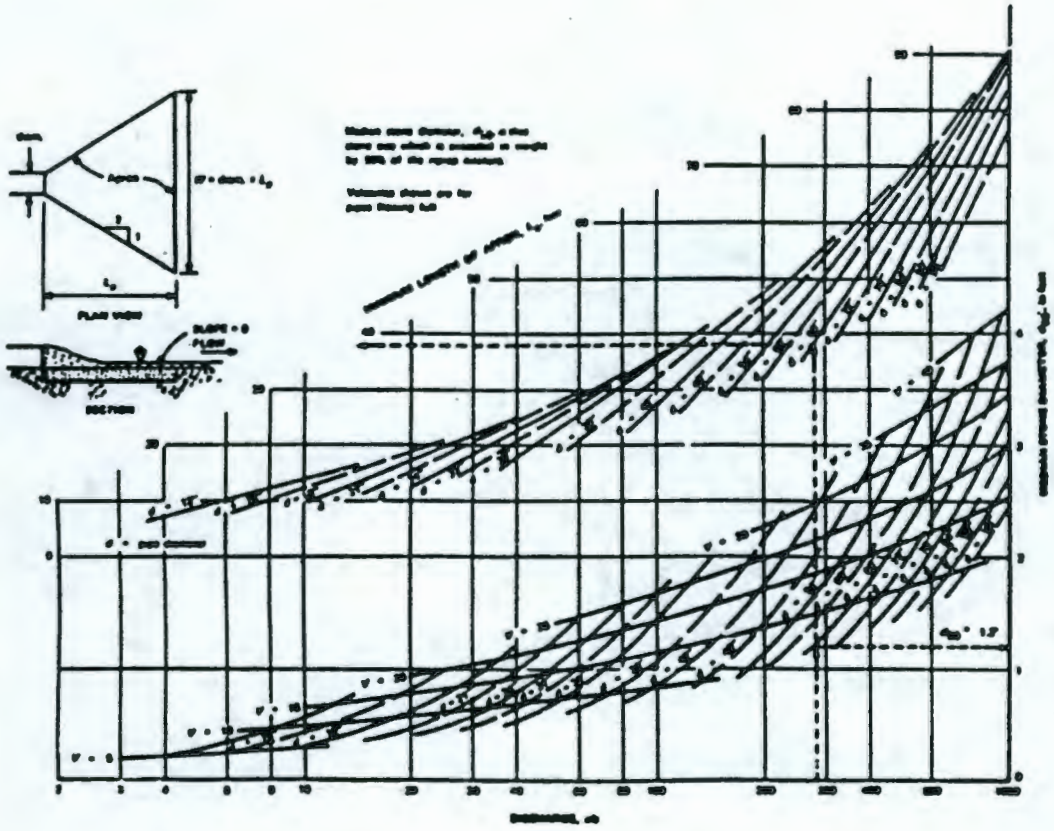
- The upstream end of the apron, adjacent to the pipe, should have a width three times the diameter of the outlet pipe.

- For a minimum tailwater condition, the downstream end of the apron will have a width equal to the pipe diameter plus the length of the apron. $W = \text{diameter} + L_a$.

- For a maximum tailwater condition, the downstream end will have a width equal to the pipe diameter plus 0.4 times the length of the apron. $W = \text{diameter} + 0.4\ L_a$.

FIGURE H-10

DESIGN OF OUTLET PROTECTION - MINIMUM TAILWATER CONDITION (T_W < 0.5 diam.)
(U. S. DEPARTMENT OF AGRICULTURE, JULY 1975)



d. Bottom grade. The apron should have no slope along its length (0.0% grade).

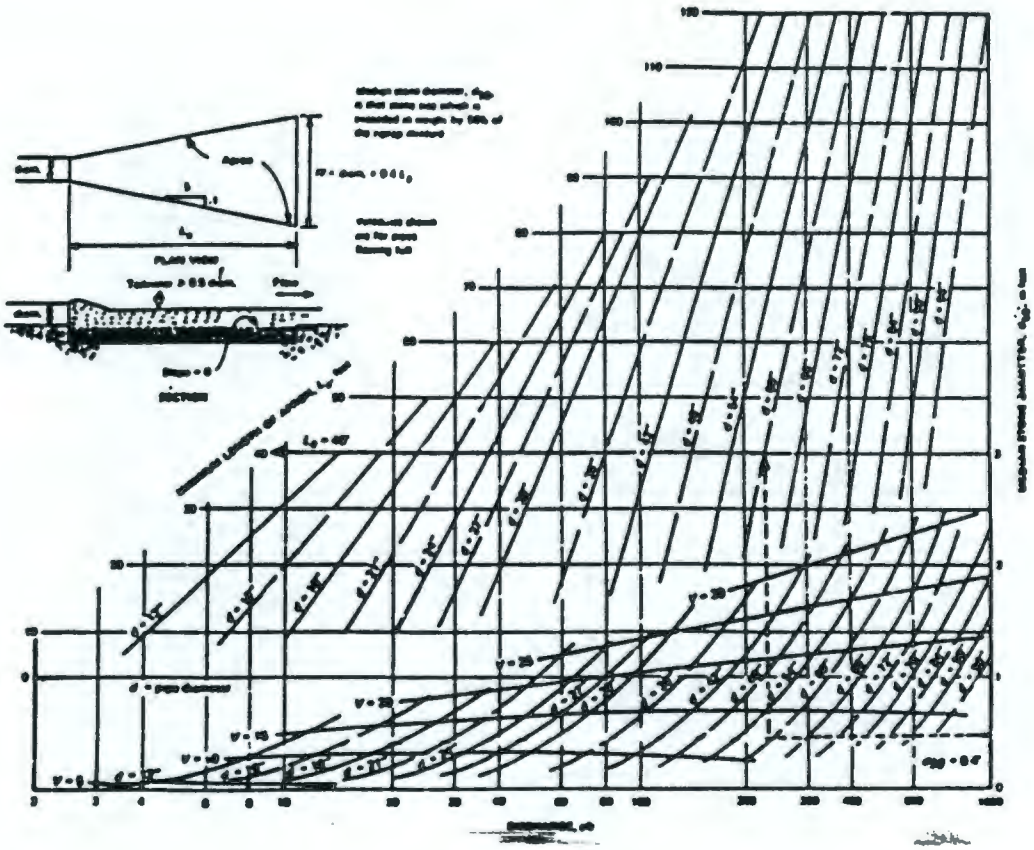
e. Side slopes. If the pipe discharges into a well-defined channel, the side slopes of the channel should not be steeper than 2:1 (horizontal:vertical).

f. Invert elevation. Invert elevation at the end should be equal to, or lower than, the lowest elevation on the cross-section immediately downstream from the end of the apron (i.e., no overfall at the end of the apron).

9 5 1 2 9 0 4 1 4 0 7

FIGURE H-11

DESIGN OF OUTLET PROTECTION - MAXIMUM TAILWATER CONDITION ($T_W \geq 0.5$ diam.)
(U. S. DEPARTMENT OF AGRICULTURE, JULY 1975)



g. Materials. Size of riprap and length of apron should be determined and riprap should meet the requirements for Riprap. Concrete paving may be substituted for the riprap. The gradation, quality, and placement of riprap should conform to Riprap.

h. Alignment. There should be no bends or curves in the horizontal alignment of the pipe and the apron unless the structure is designed to adequately handle the flow.

H.2.3 Paved Channel Outlets

The following criteria should be followed for paved channel sections (see Figure H-12):

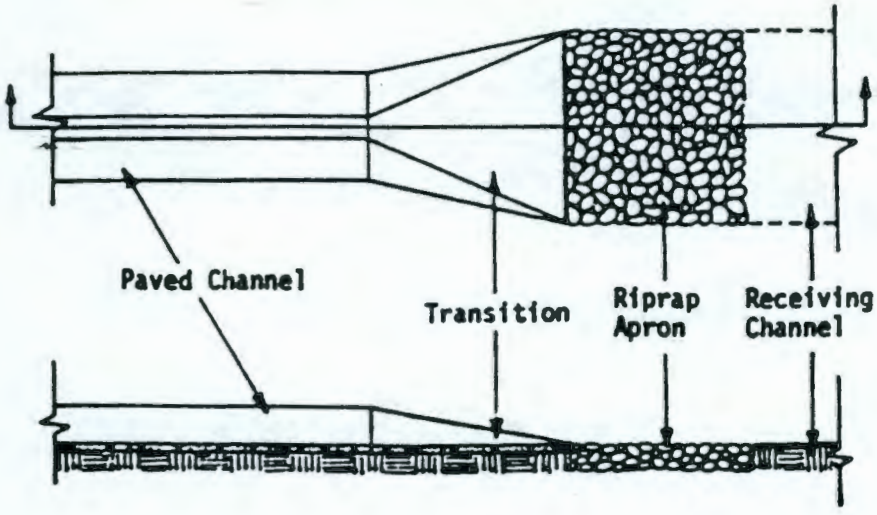
a. Velocity at the end of the paved section should be less than the allowable velocity for the succeeding downstream section.

b. The downstream end of the invert of the paved section should be no higher than the lowest point in the channel immediately downstream from the end of the paved section (i.e., no overfall at the end of the apron).

c. The end of a paved channel should merge smoothly with the next downstream channel section. This transition must be accomplished within the paved channel. The bottom width of the end of the paved channel should be at least as wide as the bottom width of the downstream channel. The maximum side divergence of a transition should be 1 in 3F, where the Froude number is given by $F = V\sqrt{gd}$, where V = the velocity, d = the depth of flow at the beginning of the transition, and g = acceleration due to gravity, 32.2 ft per sec^2.

FIGURE H-12

PAVED CHANNEL OUTLET (VSWCC, 1980)



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d. Bends or curves in the horizontal alignment of paved channels are not acceptable unless the Froude number, F, is 0.8 or less or the channel is specifically designed to contain the turbulent flow.

H.2.4 Paved Chutes

A paved chute or flume is used where a concentrated flow of surface runoff must be conveyed down a slope without causing erosion. For temporary structures built according to the following design criteria, the maximum allowable drainage area is 36 acres (U. S. Environmental Protection Agency, October 1976).

Paved flumes are an excellent means of conveying concentrated runoff from the top to the bottom of a slope without causing erosion. When used with diversion structures, paved flumes can be used to convey runoff from the entire drainage area above a slope. Permanent flumes are very useful when needed throughout the lifetime of the project. For nonpermanent slopes, temporary flumes can offer valuable protection of exposed slopes. It is very important that these structures be installed properly since their failure will often result in severe gully erosion. The entrance section should be securely entrenched, all connections should be watertight, and the conduit should be staked securely.

The following general design criteria are used for temporary structures. Permanent structures will require a formal design. See Figure H-13.

a. Size Group A

1. The height (H) of the dike at the entrance must be at least 1.5 feet.

2. The depth (d) of the chute down the slope must be at least 8 inches.

3. The length (L) of the inlet and outlet sectons must be at least 5 feet

b. Size Group B

1. The height (H) of the dike at the entrance must be at least 2 feet.

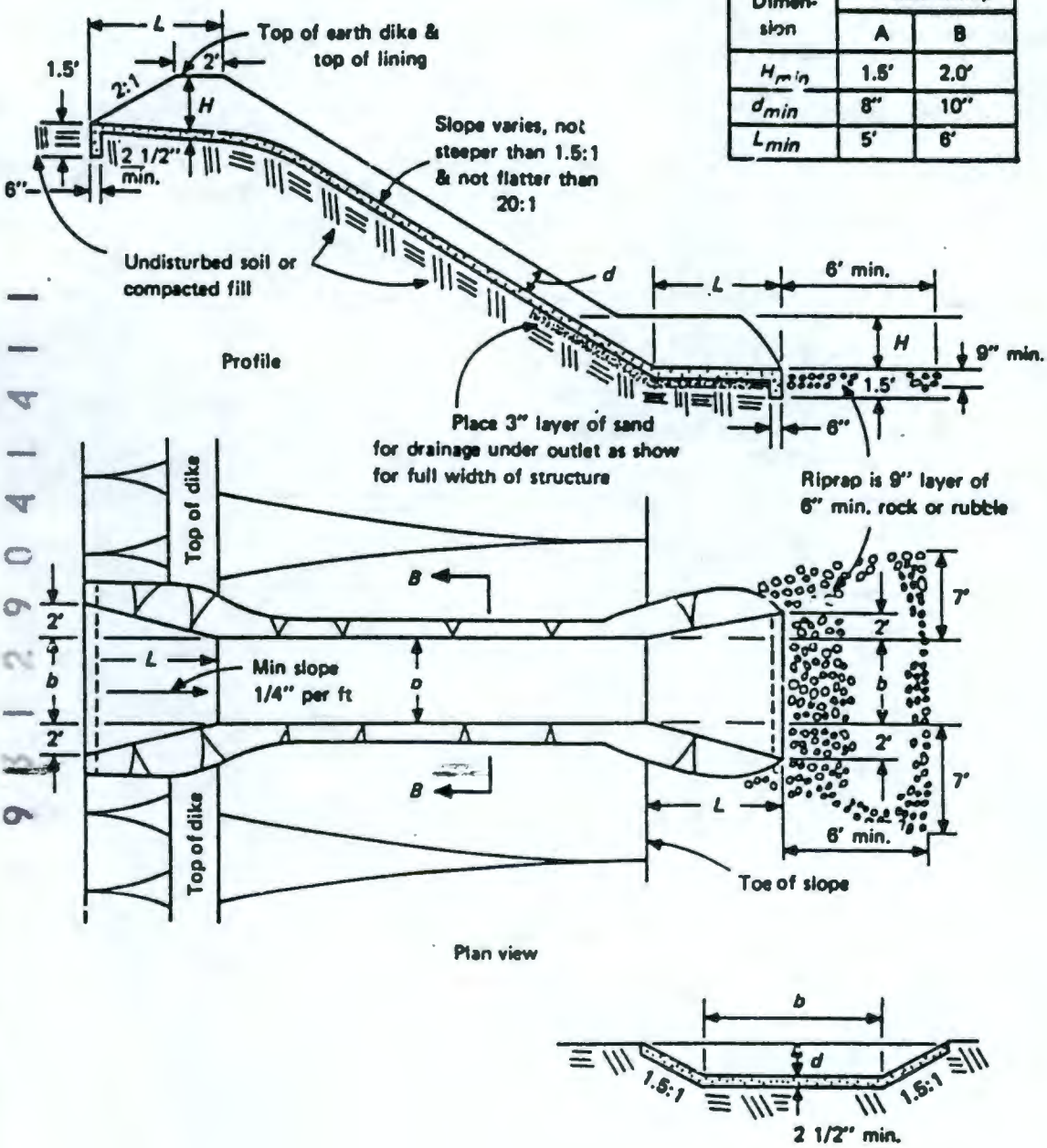
2. The depth (d) of the chute down the slope must be at least 10 inches.

3. The length (L) of the inlet and outlet sections must be at least 6 feet.

FIGURE H-13

PAVED CHUTE OR FLUME
(U. S. ENVIRONMENTAL PROTECTION AGENCY, OCTOBER 1976)

Dimension	Size Group	
	A	B
H_{min}	1.5'	2.0'
d_{min}	8"	10"
L_{min}	5'	6'



Each size group has various bottom widths and allowable drainage areas as shown in Table H-10. The drainage areas listed in Table H-10 may be increased by 50 percent if a minimum of 75 percent of the area will have good grass or woodland cover throughout the life of the structure. The same drainage areas may be increased by 25 percent if a minimum of 75 percent of the area will have a good mulch cover throughout the life of the structure.

Outlets of paved flumes must be protected from erosion. In addition, each paved flume may need an energy dissipator. Larger energy dissipators may be similarly designed for larger flume cross-sections. When a paved chute or flume of Size Group B is used the velocity at its outfall snould be checked for erosion potential downstream.

Before permanent stabilization of the slope, the structure should be inspected after each rainfall and damages to the slope or paved flume repaired immediately. After the slope is stabilized, little maintenance should be required.

TABLE H-10

BOTTOM WIDTHS AND MAXIMUM DRAINAGE AREAS
(U. S. ENVIRONMENTAL PROTECTION AGENCY, 1980)

Size[a]	Bottom width, b, (ft)	Maximum drainage area (acres)
A-2	2	5
A-4	4	8
A-6	6	11
A-8	8	14
A-10	10	18
B-4	4	14
B-6	6	20
B-8	8	25
B-10	10	31
B-12	12	36

[a]The size is designated with a letter and a number, such as A-6 which means a chute or flume in Size Group A with a 6-foot width. The selected size should appear on the plans.

H.2.5 Pipe Slope Drains

Pipe slope drains are used where a concentrated flow of surface runoff must be conveyed down a slope without causing erosion. They are also used on slopes before permanent drainage structures are installed. The maximum drainage areas for the eastern humid regions should be roughly five acres while a larger drainage area can be used for the western, more arid regions.

Temporary slope drains provide valuable protection for exposed slopes which are not stabilized and therefore particularly susceptible to erosion. These slopes are usually most vulnerable before final grading or before installation of any permanent drainage systems. When used in conjunction with diversion dikes, temporary slope drains can be used to convey stormwater from the entire drainage area above a slope to the base of the slope without erosion. It is very important that these temporary structures be installed properly since their failure will often result in severe gully erosion. The entrance section must be securely entrenched, all connections must be watertight, and the conduit must be staked securely.

Guidance for sizing of pipe slope drains is given in Table H-11. Design features of rigid and flexible pipe slope drains are shown in Figures H-14 and H-15 respectively. The earth dike height at the entrance to the pipe slope drain should be equal to, or greater than, the diameter of the pipe, D, plus 12 inches.

The pipe slope drain should outlet onto a riprap apron and then into a stabilized area or stable watercourse. Use a sediment-trapping device to trap sediment from any sediment-laden water conveyed by the pipe slope drain.

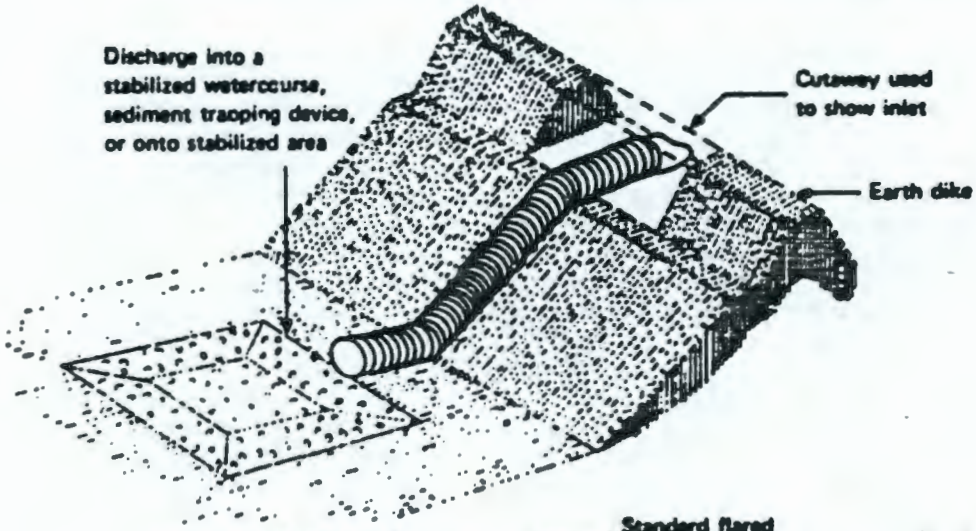
TABLE H-11

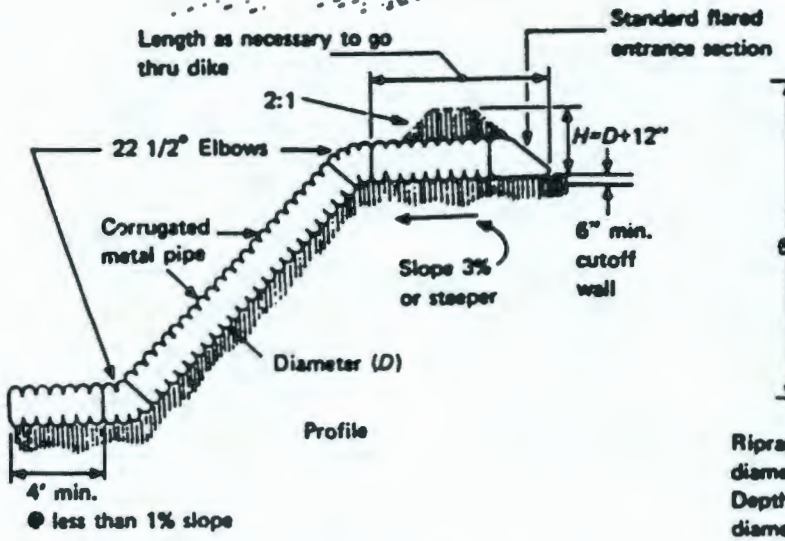
SIZE OF PIPE/TUBING
(U. S: ENVIRONMENTAL PROTECTION AGENCY, OCTOBER 1976)

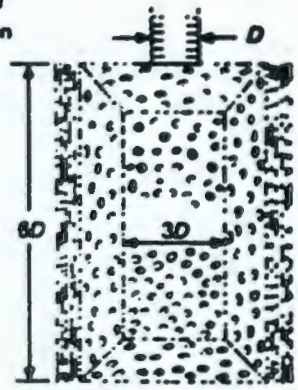
Maximum drainage area (acres)	Pipe/tubing diameter, D (in.)	Size, pipe slope drain
0.5	12	PSD-12
1.5	18	PSD-18
2.5	21	PSD-21
3.5	24	PSD-24
5.0	30	PSD-30

FIGURE H-14

PIPE SLOPE DRAIN (RIGID)
(U. S. ENVIRONMENTAL PROTECTION AGENCY, OCTOBER 1976)







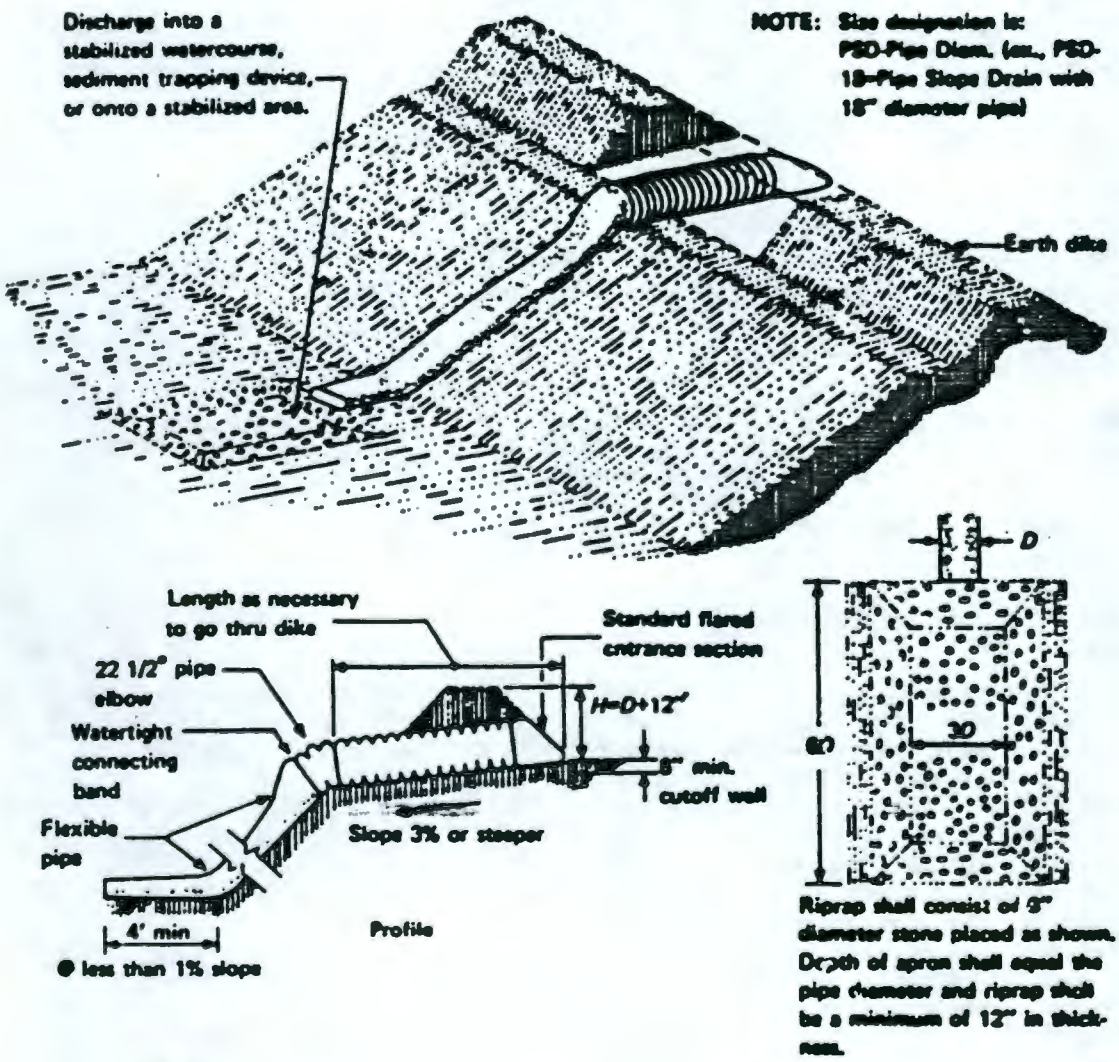
Riprap shall consist of 6" diameter stone placed as shown. Depth of apron shall equal the pipe diameter and riprap shall be a minimum of 12" in thickness.

Riprap apron plan

NOTE: Size designation is: PSD-Pipe Diam.
(ex., PSD-12=Pipe Slope Drain with 12" diameter pipe)

FIGURE H-15

PIPE SLOPE DRAIN (FLEXIBLE)
(U. S. ENVIRONMENTAL PROTECTION AGNECY, OCTOBER 1976)



The slope drain structure should be inspected weekly and after every storm for clogging or damage and repairs made, if necessary. In below-freezing weather, check to insure that sides of collapsed downdrain are not frozen together. Inlet sections should be checked for indications of piping along metal sections. Anchors should be resecured as necessary. The operator should avoid placing any material on and prevent traffic across the slope drain.

H.2.6 Channel Velocity in Unpaved Channels

Each channel reach having a natural, vegetated, or riprap-paved bottom should be checked for stability by calculating the flow velocity using Manning's equation and then assuring that the channel will handle that velocity without eroding. Field surveys will be necessary to determine cross-sections, grades, types of material in the channel, and condition of the channel.

The roughness coefficient, n, is as follows (Chow, 1959)

Channel lining	n value
Metal	
a. Smooth steel surface	
1. Unpainted	0.012
2. Painted	0.013
b. Corrugated	0.025
Metal	
a. Cement	
1. Neat, surface	0.011
2. Mortar	0.013

A plan view, profile, and cross-section of each channel reach between the storm drain outlet and receiving natural stream channel are required. Velocities should be indicated at the following: (1) outlet (pipe, structure, or paved channels), (2) riprap or paved apron section; and (3) each successive channel reach from the end of the apron to the point of entry into the existing natural stream. The proposed method of stabilizing each channel reach, consistent with computed velocities, should be shown on the plan. The velocity at the end of a structure or channel reach must not exceed the allowable velocity for the next downstream reach.

A channel reach is defined as a length of channel throughout which the hydraulic characteristics do not change. These characteristics include channel depth of flow, roughness, channel gradient, side slopes, bottom width, discharge rate, and velocity. A natural stream channel is defined as a naturally formed channel through which the storm runoff would have flowed (had there been no intervention by man) and which is capable of conveying the peak rate of runoff after development without eroding.

Outlet protection is a method which causes the expanding flow (from pipe or conduit to channel) to lose velocity and energy such that it will not erode

the next downstream channel reach. This protection is usually provided by a level apron which is designed based on curves developed for circular conduits flowing full. The curves provide the apron size and the minimum d_{50} size for riprap. There are two curves, one for a low or minimum tailwater condition (Figure H-10) and one for a high or maximum tailwater condition (Figure H-11). The minimum condition applies to a tailwater surface elevation less than the center of the pipe, whereas the maximum condition applies to a tailwater surface elevation equal to, or higher than, the center of the pipe.

The first step is to determine the tailwater condition, as discussed above. Then, for circular conduits, use the appropriate chart (Figure H-10 or H-11) and, based on the discharge and the pipe diameter, determine the riprap size and the apron length. Then calculate apron width and maximum stone size in the riprap mixture.

Example 1:

A circular conduit is flowing full.
Q = 280 cfs, diam. = 66 in., and tailwater (surface) is 2 ft above pipe invert.
This is a minimum tailwater condition (see Figure H-10)
Therefore, d_{50} = 1.2 ft, and apron length, L = 38 ft.
Apron width, W = diam. + L = 5.5 + 38 = 43.5 ft.
Maximum stone size in the riprap mixture = 2.0 x d_{50} = 2.0 x 1.2 = 2.4 ft.

In the design of outlet protection for rectangular conduits, the depth of flow and velocity are used. Determine the tailwater condition and the appropriate chart (Figure H-10 and H-11). Use the lower set of curves and, based on the velocity and depth (using the diameter curves for depth), determine d_{50} and the length of apron. To determine the apron width, substitute conduit width for diameter in the apron width equations.

Example 2:

A concrete box 5.5 ft x 10 ft is flowing 5.0 ft deep. Q = 600 cfs and the tailwater (surface) is 5 ft above invert. This is a maximum tailwater condition (see Figure H-10)

$$V \frac{Q}{A} = \frac{600}{5.0 \times 10} = 12 \text{ fps}$$

Therefore, d_{50} = 0.4 ft, and apron length, L_a = 40 ft

Apron width, W = conduit width + 0.04 L_a = 10 + (0.4) (40) 26 ft

Maximum stone size = 2.0 x d_{50} = 2.0 x 0.4 = 0.8 ft

Once the riprap installation has been completed, it should require very little maintenance. It should, however, be inspected periodically to determine if high flows have caused scour beneath the riprap or dislodged any of the stone. If repairs are needed, they should be accomplished immediately.

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APPENDIX J

INFORMATION SOURCES

The purpose of this appendix is to list certain sources of information that may be useful to the cover designer. The following types of information source are presented:

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EPA Regions	J-2
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National Climatic Center	J-7
U. S. Bureau of Reclamation	J-7
USDA State Conservation Offices	J-8
National Technical Information Center	J-10
United States Government Manual	J-10
State Geological Surveys	J-11
State Agencies responsible for Hazardous Waste Matters	J-13
Hazardous Waste Services Directory	J-16
Information Sources/Types Pertinent to HWS Investigations	J-17

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EPA REGIONS

U.S. EPA Region 1
Solid Waste Program
John F. Kennedy Bldg.
Boston, MA 02203
617-223-6883

U.S. EPA Region 2
Solid Waste Section
26 Federal Plaza
New York, NY 10007
212-264-0504

U.S. EPA, Region 3
Solid Waste Program
841 Chestnut St.
Philadelphia, PA 19106
215-597-8131

U.S. EPA Region 4
Solid Waste Program
345 Courtland St., N.E.
Atlanta, GA 30365
404-881-3016

U.S. EPA, Region 5
Solid Waste Program
230 South Dearborn St.
Chicago, IL 60604
312-886-7435

U.S. EPA, Region 6
Solid Waste Section
1201 Elm St.
Dallas, TX 75270
214-767-2645

U.S. EPA Region 7
Solid Waste Section
726 Minnesota Ave.
Kansas City, MO 66101
816-374-6529

U.S. EPA, Region 8
Solid Waste Section
999 18th Street, Suite 1300
One Denver Place
Denver CO 80202
303-564-1662

U.S. EPA, Region 9
Solid Waste Program
215 Fremont St.
San Francisco, CA 94105
415-974-7460

U.S. EPA Region 10
Solid Waste Program
1200 6th Ave.
Seattle, WA 98101
206-442-2808

U. S. Geological Survey (USGS)

Since 1879, the USGS has collected, analyzed, and published detailed information about the Nation's mineral, land, and water resources. Compiled information is available in a variety of map, book, and other formats. An annually updated "Guide to Obtaining Information from the USGS - Circular 777" gives a complete listing of sources where USGS products may be obtained, and is available from the following sources:

Eastern Distribution Branch
U.S. Geological Survey
1200 South Eads Street
Arlington, VA 22202

(703) 557-2781
FTS 557-2781

Text Products Section
Eastern Distribution Branch
U.S. Geological Survey
604 South Pickett Street
Alexandria, VA 22304-4658

(703) 756-6141
FTS 756-6141

Public Inquiries Office
U.S. Geological Survey
108 Skyline Building
508 West Second Avenue
Anchorage, AK 99501

(907) 277-0577
FTS 8-907-277-0577

Public Inquiries Office
U.S. Geological Survey
7638 Federal Building
300 North Los Angeles Street
Los Angeles, CA 90012

(213) 688-2850
FTS 798-2850

Public Inquiries Office
U.S. Geological Survey
Building 3, Room 122
Mail Stop 33
345 Middlefield Road
Menlo Park, CA 94025

(415) 323-8111 ext. 2818
FTS 467-2818

Public Inquiries Office
U.S. Geological Survey
504 Custom House
555 Battery Street
San Francisco, CA 94111

(415) 556-5627
FTS 556-5627

Public Inquiries Office
U.S. Geological Survey
169 Federal Building
1961 Stout Street
Denver, CO 80294

(303) 837-4169
FTS 327-4169

Public Inquiries Office
U.S. Geological Survey
1028 General Services Administration Building
19th and F Streets, NW.
Washington, DC 20244

(202) 343-8073
FTS 343-8073

Public Inquiries Office
U.S. Geological Survey
1-C-45 Federal Building
1100 Commerce Street
Dallas, TX 75242

(214) 767-0198
FTS 729-0198

Public Inquiries Office
U.S. Geological Survey
8105 Federal Building
125 South State Street
Salt Lake City, UT 84138

(801) 524-5652
FTS 588-5652

9 3 1 2 9 0 4 1 4 3 1

Public Inquiries Office
U.S. Geological Survey
503 National Center
Room 1-C-402
12201 Sunrise Valley Drive
Reston, VA 22092

(703) 860-6167
FTS 928-6167

Public Inquiries Office
U.S. Geological Survey
678 U.S. Court House
West 920 Riverside Avenue
Spokane, WA 99201

(509) 456-2524
FTS 439-2524

Don Lee Kulow Memorial Library
EROS Data Center
Sioux Falls, SD 57198

(605) 594-6114
FTS 784-7114

Library
U.S. Geological Survey
Mail Stop 55
345 Middlefield Road
Menlo Park, CA 94025

(415) 323-8111 ext. 2207
FTS 467-2207

Library
U.S. Geological Survey
Box 25046, Federal Center
Mail Stop 914
Denver, CO 80225

(303) 234-4133
FTS 234-4133

Street address:

Denver West Office Park, Building 3
1526 Cole Boulevard
Golden, CO 80401

Library
U.S. Geological Survey
2255 North Gemini Drive
Flagstaff, AZ 86001

(602) 779-3311 ext. 1386
FTS 261-1386

Library
U.S. Geological Survey
950 National Center
Room 4-A-100
12201 Sunrise Valley Drive
Reston, VA 22092

(703) 860-6671
FTS 928-6671

The USGS Water Resources Division has district offices in each state, which may supply information on hydrogeologic studies conducted in the area of aHWS. The following list contains addresses and telephone numbers for the State District Offices.

Alabama

P.O. Box V
302 Oil & Gas Board Building
University of Alabama
University, AL 35486

(205) 752-8104
FTS 229-2967

Alaska

733 West Fourth Avenue
Suite 400
Anchorage, AK 99501

(907) 271-4136
FTS 8-907-271-4136

Arizona

Federal Building
FB 44
301 West Congress Street
Tucson, AZ 85701-1393

(602) 792-6671
FTS 762-6671

Arkansas

2301 Federal Office Building
700 West Capitol Avenue
Little Rock, AR 72201

(501) 378-6391
FTS 740-6391

California

855 Oak Grove Avenue
Menlo Park, CA 94025

(415) 323-8111, ext. 2326
FTS 467-2326

Colorado

Box 25046, Federal Center
Mail Stop 415
Denver, CO 80225

(303) 234-5092
FTS 234-5092

Connecticut

525 Abraham A. Ribicoff Federal Building
450 Main Street
Hartford, CT 06103

(203) 244-2528
FTS 244-2528

Delaware

See listing for Maryland

District of Columbia

See listing for Maryland

Florida

325 John Knox Road
Suite F-240
Tallahassee, FL 32303-4181

(904) 386-1118
FTS 8-904-386-7145

Georgia

6481 Peachtree Industrial Boulevard
Suite B
Doraville, GA 30360

(404) 221-4858
FTS 242-4858

Hawaii

P.O. Box 50166
300 Ala Moana Boulevard
Room 6110
Honolulu, HI 96850

(808) 546-8331
FTS 8-808-546-8331

Idaho

Box 036, Federal Building
Room 365, 550 West Fort Street
Boise, ID 83724

(208) 334-1750
FTS 554-1750

Illinois

Champaign County Bank Plaza
102 East Main, 4th Floor
Urbana, IL 61801

(217) 398-5353
FTS 958-5353

Indiana

6023 Guion Road
Suite 201
Indianapolis, IN 46254

(317) 927-8640
FTS 336-8640

Iowa

P.O. Box 1230
269 Federal Building
400 South Clinton Street
Iowa City, IA 52244

(319) 337-4191
FTS 863-6521

Kansas

1950 Avenue A—Campus West
University of Kansas
Lawrence, KS 66044

(913) 864-4321
FTS 752-2300

Kentucky

572 Federal Building
600 Federal Place
Louisville, KY 40202

(502) 582-5241
FTS 352-5241

Louisiana

P.O. Box 66492
6554 Florida Boulevard
Baton Rouge, LA 70896

(504) 389-0281
FTS 687-0281

Maine

150 Causeway Street
Suite 1001
Boston, MA 02114

(617) 223-2822
FTS 223-2822

Maryland

208 Carroll Building
8600 LaSalle Road
Towson, MD 21204

(301) 828-1535
FTS 922-7872
(Ask operator for 828-1535)

Massachusetts

See listing for Maine

Michigan

6520 Mercantile Way
Suite 5
Lansing, MI 48910

(517) 377-1608
FTS 374-1608

Minnesota

702 Post Office Building
St. Paul, MN 55101

(612) 725-7841
FTS 725-7841

Mississippi

100 West Capitol Street
Suite 710, Federal Building
Jackson, MS 39201

(601) 960-4600
FTS 490-4600

Missouri

1400 Independence Road
Mail Stop 200
Rolla, MO 65401

(314) 341-0824
FTS 277-0824

93129041433

Montana

301 South Park Avenue
428 Federal Building
Drawer 10076
Helena, MT 59601

(406) 449-5263
FTS 585-5263

Nebraska

406 Federal Building and U.S. Courthouse
100 Centennial Mall North
Lincoln, NE 68508

(402) 471-5082
FTS 541-5082

Nevada

229 Federal Building
705 North Plaza Street
Carson City, NV 89701

(702) 882-1386
FTS 470-5011
(Ask operator for 882-1386)

New Hampshire

See listing for Maine

New Jersey

430 Federal Building
402 East State Street
Trenton, NJ 08608

(609) 989-2162
FTS 483-2162

New Mexico

P.O. Box 26659
815 Western Bank Building
505 Marquette, Northwest
Albuquerque, NM 87125

(505) 766-2246
FTS 474-2246

New York

P.O. Box 1350
343 U.S. Post and Courthouse Building
Albany, NY 12201

(518) 472-3107
FTS 562-3107

North Carolina

P.O. Box 2857
436 Century Station Post Office Building
Raleigh, NC 27602

(919) 755-4510
FTS 672-4510

North Dakota

821 East Interstate Avenue
Bismarck, ND 58501

(701) 256-4011, ext. 601
FTS 783-4601

Ohio

975 West Third Avenue
Columbus, OH 43212

(614) 469-5663
FTS 943-5663

Oklahoma

215 Dean A. McGee Avenue
Room 621
Oklahoma City, OK 73102

(405) 231-4256
FTS 736-4256

Oregon

P.O. Box 3202
830 NE Holladay Street
Portland, OR 97208

(503) 231-2009
FTS 429-2009

Pennsylvania

P.O. Box 1107
Federal Building, 4th Floor
228 Walnut Street
Harrisburg, PA 17108

(717) 782-4614
FTS 590-4614

Puerto Rico

GPO Box 4464
San Juan, PR 00936

(809) 753-4660
FTS 8-809-753-4414

Rhode Island

See listing for Maine

South Carolina

Strom Thurmond Federal Building
1835 Assembly Street
Suite 658
Columbia, SC 29201

(803) 765-5696
FTS 677-5696

South Dakota

317 Federal Building
200 Fourth Street, Southwest
Huron, SD 57350

(605) 352-8651, ext. 256
FTS 782-2256

Tennessee

A-433 Federal Building and U.S. Courthouse
Nashville, TN 37203

(615) 251-5424
FTS 852-5424

Texas

649 Federal Building
300 East Eighth Street
Austin, TX 78701

(512) 397-5766
FTS 734-5766

Utah

Room 1016 Administration Building
1745 West 1700 South
Salt Lake City, UT 84104

(801) 524-5663
FTS 588-5663

Vermont

See listing for Maine

Virginia

200 West Grace Street
Room 304
Richmond, VA 23220

(804) 771-2427
FTS 925-2427

Washington

1201 Pacific Avenue
Suite 600
Tacoma, WA 98402

(206) 593-6510
FTS 390-6510

West Virginia

3017 Federal Building and U.S. Courthouse
500 Quarrier Street, East
Charleston, WV 25301

(304) 343-5161, ext. 310
FTS 924-1310

Wisconsin

1819 University Avenue
Room 200
Madison, WI 53706

(608) 262-2488
FTS 262-2488

Wyoming

P.O. Box 1125
4007 J. C. O'Mahoney Federal Center
2120 Capitol Avenue
Cheyenne, WY 82003

(307) 778-2220, ext. 2153
FTS 328-2153

9 3 1 2 9 0 4 1 4 3 5

National Climatic Center

The address of the National Climatic Center is:

National Climatic Center
Federal Building
Asheville, NC 28801

(704) 258-2850, ext. 683
FTS 672-0683

U. S. Bureau of Reclamation

Drawings cited in USBR publications may be obtained from the following office:

Bureau of Reclamation
ATTN: D-235
P. O. Box 25007
Denver, CO 80225

(303) 234-3022
FTS 234-3022

STATE CONSERVATION OFFICES, U. S. DEPARTMENT OF AGRICULTURE
(SOURCE: SISK, 1981)

ALABAMA, Auburn 36830
Wright Building
138 South Gay Street
P.O. Box 311
Phone: 534-4535 (FTS)
205-821-8070 (CML)

ALASKA, Anchorage 99504
Suite 129, Professional Bldg.
2221 E. Northern Lights Blvd.
Phone: 907-276-4246 (FTS & CML)[a]

ARIZONA, Phoenix 85025
230 N. 1st Avenue
3008 Federal Building
Phone: 602-261-6711 (FTS & CML)

ARKANSAS, Little Rock 72203
Federal Building, Room 5029
700 West Capitol Street
P.O. Box 2323
Phone: 740-5445 (FTS)
501-378-5445 (CML)

CALIFORNIA, Davis 95616
2828 Chiles Road
Phone: 916-758-2200 ext. 210
(FTS & CML)

COLORADO, Denver 80217
2490 W. 26th Avenue
P.O. Box 17107
Phone: 327-4275 (FTS)
303-837-4275 (CML)

CONNECTICUT, Storrs 06268
Mansfield Professional Park
Route 44A
Phone: 244-2547/2548 (FTS)
203-429-9361/9362 (CML)

DELAWARE, Dover 19901
Treadway Towers, Suite 2-4
9 East Loockerman Street
Phone: 487-5140 (FTS)
302-678-0750 (CML)

FLORIDA, Gainesville 32602
Federal Building
P.O. Box 1208
Phone: 946-3071 ext. 100 (FTS)
904-377-8732 (CML)

GEORGIA, Athens 30603
Federal Building
355 E. Hancock Avenue
P.O. Box 832
Phone: 250-2275 (FTS)
404-546-2274 (CML)

HAWAII, Honolulu 96850
300 Ala Moana Blvd.
Room 4316
P.O. Box 5004
Phone: 808-546-3165 (FTS & (CML)[b]

IDAHO, Boise 83702
304 North 8th Street, Room 345
Phone: 554-1601 (FTS)
208-384-1601 ext 1601 (CML)

ILLINOIS, Champaign 61820
Federal Building
200 W. Church Street
P.O. Box 678
Phone: 958-5271 (FTS)
217-356-3785 (CML)

INDIANA, Indianapolis 46224
Atkinson Square-West Suite 2200
5610 Crawfordsville Road
Phone: 331-6515 (FTS)
317-269-3785 (CML)

IOWA, Des Moines 50309
693 Federal Building
210 Walnut Street
Phone: 515-862-4260 (FTS & CML)

KANSAS, Salina 67401
760 South Broadway
P.O. Box 600
Phone: 752-4753 (FTS)
913-825-9535 (CML)

KENTUCKY, Lexington 40504
333 Waller Avenue
Phone: 355-2749 (FTS)
606-233-2749 ext 2749 (CML)

LOUISIANA, Alexandria 71301
3737 Government Street
P.O. Box 1630
Phone: 497-6611 ext 233 (FTS)
318-448-3421 (CML)

MAINE, Orono 04473
USDA Building
University of Maine
Phone: 833-7393 (FTS)
207-866-2132/2133 (CML)

MARYLAND, College Park 20740
Room 522, Hartwick Building
4321 Hartwick Road
Phone: 301-344-4180 (FTS & CML)

MASSACHUSETTS, Amherst 01002
29 Cottage Street
Phone: 413-549-0650 (FTS & CML)[c]

MICHIGAN, East Lansing 48823
1405 South Harrison Road
Room 101
Phone: 374-4242 (FTS)
517-372-1910 ext 242 (CML)

MINNESOTA, St. Paul 55101
200 Federal Bldg & U.S. Courthouse
316 North Robert Street
Phone: 612-725-7675 (FTS & CML)

MISSISSIPPI, Jackson 39205
Milner Building, Room 590
210 South Lamar Street
P.O. Box 610
Phone: 490-4335 (FTS)
601-969-4330 (CML)

MISSOURI, Columbia 65201
555 Vandiver Drive
Phone: 276-3145 (FTS)
314-442-2271 ext 3155 (CML)

MONTANA, Bozeman 59715
Federal Building
P.O. Box 970
Phone: 585-4322 (FTS)
406-587-5271 ext 4322 (CML)

NEBRASKA, Lincoln 68508
Federal Building
U.S. Courthouse, Room 345
Phone: 541-5300 (FTS)
402-471-5301 (CML)

NEVADA, Reno 89505
U.S. Post Office Bldg. Rm 308
P.O. Box 4850
Phone: 470-5304 (FTS)
702-784-5304 CML)

NEW HAMPSHIRE, Durham 03824
Federal Building
Phone: 834-0505 (FTS)
603-868-7581 (CML)

NEW JERSEY, Somerset 08873
1370 Hamilton Street
P.O. Box 219
Phone: 342-5341
201-246-1205 ext 20 (CML)

NEW MEXICO, Albuquerque 87103
517 Gold Avenue, SW
P.O. Box 2007
Phone: 474-2173 (FTS)
505-766-2173 (CML)

NEW YORK, Syracuse 13260
U.S. Courthouse & Federal Bldg.
100 S. Clinton Street, Room 771
Phone: 950-5494 (FTS)
315-423-5493 (CML)

NORTH CAROLINA, Raleigh 27611
310 New Bern Ave, Federal Bldg
Room 544 P.O. Box 27307
Phone: 672-4210 (FTS)
919-755-4165 (CML)

NORTH DAKOTA, Bismarck 58501
Federal Bldg. - Rosser Ave & 3rd St.
P.O. Box 1458
Phone: 783-4421 (FTS)
701-255-4011 ext 421 (CML)

OHIO, Columbus 43215
200 No. High St, Room 522
Phone: 943-6962 (FTS)
614-469-6785 (CML)

OKLAHOMA, Stillwater 74074
Agriculture Building
Farm Road & Brumley Street
Phone: 728-4360 (FTS)
405-624-4360 (CML)

OREGON, Portland 97209
Federal Office Building
1220 SW 3rd Avenue
Phone: 423-2751 (FTS)
503-221-2751 (CML)

STATE CONSERVATION OFFICES (continued)

PENNSYLVANIA, Harrisburg 17108
Federal Bldg. & Courthouse
Box 908 Federal Square Station
Phone: 590-2202 (FTS)
717-782-4403 (CML)

PUERTO RICO, Hato Rey 00918
Federal Office Bldg. Room 633
Mail: GPO Box 4868
PUERTO RICO, San Juan 00936
Phone: 809-753-4206[d]

RHODE ISLAND, West Warwick 02893
46 Quaker Lane
Phone: 401-828-1300 (FTS)[e]

SOUTH CAROLINA, Columbia 29210
240 Stoneridge Drive
Phone: 677-5681 (FTS)
803-765-5681 (CML)

SOUTH DAKOTA, Huron 57350
Federal Bldg 200 4th St. SW
P.O. Box 1357
Phone: 782-2333 (FTS)
605-352-8651 (CML)

TENNESSEE, Nashville 37203
675 U.S. Courthouse
Phone: 852-5471 (FTS)
615-749-5471 (CML)

TEXAS, Temple 76501
W.R. Poage Federal Building
101 S. Main St. P.O. Box 648
Phone: 736-1214 (FTS)
817-773-1711 ext 331 (CML)

UTAH, Salt Lake City 84138
4012 Federal Bldg - 125 S. State St.
Phone: 588-5050 (FTS)
801-524-5051 (CML)

VERMONT, Burlington 05401
1 Burlington Square, Suite 205
Phone: 832-6794 (FTS)
802-862-6501 ext 6261 (CML)

VIRGINIA, Richmond 23240
Federal Bldg., Room 9201
400 N. 8th Street - P.O. Box 10026
Phone: 925-2457 (FTS)
804-782-2457 (CML)

WASHINGTON, Spokane 99201
360 U.S. Courthouse
W. 920 Riverside Avenue
Phone: 439-3711 (FTS)
509-456-3711 (CML)

WEST VIRGINIA, Morgantown 26505
75 High Street, P.O. Box 865
Phone: 923-7151 (FTS)
304-599-7151 (CML)

WISCONSIN, Madison 53711
4601 Hammersley Road
Phone: 364-5351 (FTS)
608-252-5351 (CML)

WYOMING, Casper 82601
Federal Office Bldg, P.O. Box 2440
Phone: 328-5201 (FTS)
307-265-5550 ext 3217 (CML)

TECHNICAL SERVICE CENTERS

MIDWEST

NEBRASKA, Lincoln 68508
Federal Bldg.-U.S. Courthouse, Rm 393
Phone: 541-5346 (FTS)
402-471-5361 (CML)

WEST

OREGON, Portland 97209
511 N.W. Broadway
Phone: 423-2824 (FTS)
503-221-2824 (CML)

NORTHEAST

PENNSYLVANIA, Broomall 19008
1974 Sproul Road
Phone: 596-5783 (FTS)
215-596-5710 (CML)

SOUTH

TEXAS, Ft. Worth 76115
Ft. Worth Federal Center
P.O. Box 6567
Phone: 817-334-5456 (FTS & CML)

CARTOGRAPHIC UNITS

(Not located at TSC)

MARYLAND, Lanham 20782
10000 Aerospace Road
Phone: 301-436-8756 (FTS & CML)

FOOTNOTES

FTS = Federal Telecommunications System Number

CML = Commercial Number

a = Calls to Anchorage, Alaska are made:

Through FTS Seattle, Washington, 399-0150 between 7:30 am - 6:00 pm PST

Through FTS Washington, D.C. (Except Washington, D.C.) 967-1221 when Seattle FTS closed

b = Calls to Hawaii are made:

Through FTS San Francisco, Calif. 556-0220 between 7:00 am - 3:00 pm PST

Through FTS Washington, D.C. (Except Washington, D.C.) 967-1221 when S. F. FTS closed

c = Calls to Amherst are made by calling FTS Boston 223-2100[g]

d = Calls to Puerto Rico are made:

Through Washington, D.C.[g]
202 9-472-6620
From Washington, D.C.
9-472-6620
This is access to overseas operator--then give number desired

e = Calls to West Warwick by calling FTS Providence 528-1000[g]

f = Washington, D.C., calls to Alaska, Hawaii, and Puerto Rico see FTS Users Guide

g = For direct dialing from Washington, D.C. (Hyattsville included) to Amherst and Providence, dial Access Code "8," area code, and number listed for State Conservationist

October 1980

The National Technical Information Service (NTIS)

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Documents ordered from NTIS must be ordered by their NTIS document number. A typical document number would be PB81-166365. The report having this NTIS document number would have entered the NTIS collection in 1981, and would the 166365th sequential entry during that year. If the NTIS document number is not known, it must be obtained from the NTIS library.

Address and phone numbers of NTIS are as follows:

U. S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

(703) 487-4600 (General Information)
(703) 487-4650 (New Orders for Documents and Reports)
(703) 487-4780 (Library)

The United States Government Manual

The USGM is the official handbook of the Federal Government and provides comprehensive information on the agencies of the legislative, judicial, and executive branches. Revised annually, it is sold by the Superintendent of Documents, Government Printing Office.

Among the wide-ranging information in the USGM are descriptive summaries, addresses, telephone numbers, and listings of key personnel of various agencies. It also describes the Standard Federal Regions.

1980 DIRECTORY

ASSOCIATION OF AMERICAN STATE GEOLOGISTS
(SOURCE: SISK, 1981)

ALABAMA (205)349-2852
Thomas J. Joiner
Geol. Survey of Alabama
P. O. Drawer O
University, AL 35486

ALASKA (907)279-1433
Ross G. Schaff
Div. of Geology and
Geophysical Surveys
3001 Porcupine Drive
Anchorage, AK 99501

ARIZONA (602)626-2733
Larry D. Fellows
Bureau of Geology and
Mineral Technology
Geological Survey Branch
845 N. Park Ave.
Tucson, AZ 85719

ARKANSAS (501)371-1488
Norman F. Williams
Arkansas Geol. Commission
Vardelle Parham Geol. Center
3815 W. Roosevelt Road
Little Rock, AR 72204

CALIFORNIA (916)445-1923
James F. Davis
Div. of Mines & Geology
Calif. Dept. of Conservation
1416 9th St., Room 1341
Sacramento, CA 95814

COLORADO (303)839-2611
John W. Rold
Colorado Geological Survey
1313 Sherman St., Room 715
Denver, CO 80203

CONNECTICUT (203)566-3540
Hugo F. Thomas
Conn. Geol. & Natural
History Survey
State Office Bldg., Room 553
165 Capitol Ave.
Hartford, CT 06115

DELAWARE (302)738-2833
Robert R. Jordan
Delaware Geological Survey
University of Delaware
Newark, DE 19711

FLORIDA (904)488-4191
Charles W. Hendry, Jr.
Bureau of Geology
903 W. Tennessee St.
Tallahassee, FL 32304

GEORGIA (404)656-3214
William McLemore
Geol. & Water Resources Div.
Dept. of Natural Resources
19 Dr. Martin Luther King,
Jr. Drive, S.W.
Atlanta, GA 30334

HAWAII (808)548-7533
Robert T. Chuck
Div. of Water & Land Develop.
Dept. of Land & Natural Res.
P. O. Box 373
Honolulu, HI 96809

IDAHO (208)885-6785
Maynard M. Miller
Idaho Bur. of Mines & Geol.
Moscow, ID 83843

ILLINOIS (217)333-5111
Jack A. Simon
Illinois State Geol. Survey
121 Natural Resources Bldg.
Urbana, IL 61801

INDIANA (812)337-2862
John B. Patton
Dept. of Natural Resources
Indiana Geological Survey
611 North Walnut Grove
Bloomington, IN 47401

IOWA (319)338-1173
Stanley C. Grant
Iowa Geological Survey
123 N. Capitol
Iowa City, IA 52242

KANSAS (913)864-3965
William W. Hambleton
State Geol. Survey of Kansas
Raymond C. Moore Hall
1930 Ave. A, Campus West
Lawrence, KS 66044

KENTUCKY (606)622-3270
Donald C. Haney
Kentucky Geological Survey
University of Kentucky
311 Breckinridge Hall
Lexington, KY 40506

LOUISIANA (504)342-6754
Charles G. Groat
Louisiana Geological Survey
Box G, Univ. Station
Baton Rouge, LA 70893

MAINE (207)289-2801
Walter Anderson
Maine Geological Survey
State Office Bldg., Room 211
Augusta, ME 04330

MARYLAND (301)235-0771
Kenneth N. Weaver
Maryland Geological Survey
Merryman Hall
Johns Hopkins University
Baltimore, MD 21218

MASSACHUSETTS (617)727-4793
Joseph A. Sinnott
Dept. of Environmental
Quality Engineering
Div. of Waterways - Room 532
100 Nashua St.
Boston, MA 02114

MICHIGAN (517)373-1256
Arthur E. Slaughter
Michigan Dept. of Natural Res.
Geological Survey Division
P. O. Box 30028
Lansing, MI 48909

MINNESOTA (612)373-3372
Matt Walton
Minnesota Geological Survey
1633 Eustis Street
St. Paul, MN 55108

MISSISSIPPI (601)354-6228
William H. Moore
Miss. Geol., Econ., &
Topo. Survey
P. O. Box 4915
Jackson, MS 39216

MISSOURI (314)364-1752
Wallace B. Howe
Div. of Geol. & Land Survey
P. O. Box 250
Rolla, MO 65401

MONTANA (406)792-8321
Sid Groff
Mont. Bur. of Mines & Geol.
Montana College of Mineral
Science and Technology
Butte, MT 59701

NEBRASKA (402)472-3471
Vincent H. Dreeszen
Conservation & Survey Div.
University of Nebraska
Lincoln, NE 68508

NEVADA (702)784-6691
John Schilling
Nevada Bur. of Mines &
Geology
University of Nevada
Reno, NV 89557

NEW HAMPSHIRE (603)862-1216
Glenn W. Stewart
Office of State Geologist
James Hall
Univ. of New Hampshire
Durham, NH 03824

NEW JERSEY (609)292-2576
Kemble Widmer
New Jersey Bureau of
Geology & Topography
P. O. Box 1390
Trenton, NJ 08625

NEW MEXICO (505)835-5420
Frank E. Kottlowski
New Mexico Bur. of Mines
& Mineral Resources
New Mexico Tech
Socorro, NM 87801

NEW YORK (518)474-5816
Robert H. Fakundiny
New York State Geol. Survey
State Education Building
Albany, NY 12234

NORTH CAROLINA (919)733-3833
Stephen G. Conrad
North Carolina Dept. of Nat.
Res. & Community Develop.
P. O. Box 27687
Raleigh, NC 27611

NORTH DAKOTA (701)777-2231
Lee C. Gerhard
North Dakota Geol. Survey
University Station
Grand Forks, ND 58202

OHIO (614)466-5344
Horace R. Collins
Ohio Div. of Geol. Survey
Fountain Square, Bldg. B
Columbus, OH 43224

OKLAHOMA (405)325-3031
Charles J. Mankin
Oklahoma Geological Survey
830 Van Vleet Oval, Rm. 163
Norman, OK 73019

OREGON (503)229-5580
Donald A. Hull
State Dept. of Geology &
Mineral Industries
1069 State Office Bldg.
1400 SW Fifth Avenue
Portland, OR 97201

PENNSYLVANIA (717)787-2169
Arthur A. Socolow
Bur. of Topo. & Geol. Survey
Dept. of Envir. Resources
P. O. Box 2357
Harrisburg, PA 17120

PUERTO RICO (809)722-3142
Director
Servicio Geologico de P. R.
Dept. de Recursos Naturales
Apartado 5887, Puerta de
Tierra
San Juan, PR 00906

RHODE ISLAND
Robert L. McMaster
Assoc. State Geologist for
Marine Affairs
Grad. School of Oceanography
Kingston, RI 02881

SOUTH CAROLINA (803)758-6431
Norman K. Olson
South Carolina Geol. Survey
State Development Board
Harbison Forest Road
Columbia, SC 29210

SOUTH DAKOTA (605)624-4471
Duncan J. McGregor
S.D. State Geol. Survey
Science Center
Univ. of South Dakota
Vermillion, SD 57069

TENNESSEE (615)741-2726
Robert E. Hershey
Dept. of Conservation
Division of Geology
G-5 State Office Bldg.
Nashville, TN 37219

TEXAS (512)471-1534
W. L. Fisher
Bureau of Economic Geology
University Station, Box X
Austin, TX 78712

UTAH (801)581-6831
Donald T. McMillan
Utah Geol. & Mineral Survey
606 Black Hawk Way
Salt Lake City, UT 84108

VERMONT (802)828-3357
Charles A. Ratte
Agency of Environmental
Conservation
5 Court Street
Montpelier, VT 05602

VIRGINIA (804)293-5121
Robert C. Milici
Virginia Div. of Mineral Res.
P. O. Box 3667
Charlottesville, VA 22903

WASHINGTON (206)753-6183
Vaughn E. Livingston, Jr.
Dept. of Natural Resources
Geol. & Earth Resources Div.
Olympia, WA 98504

WEST VIRGINIA (304)292-6331
Robert B. Erwin
W. Va. Geol. & Econ. Survey
P. O. Box 879
Morgantown, WV 26505

WISCONSIN (608)262-1705
Meredith E. Ostrom
Wisc. Geol. & Natural
History Survey
1815 University Ave.
Madison, WI 53706

WYOMING (307)742-2054
Daniel N. Miller, Jr.
Wyoming Geological Survey
Box 3008, Univ. Station
Laramie, WY 82071

State Agencies Responsible for Hazardous Waste Matters*

Division of Solid and Hazardous Waste
Department of Public Health
Public Health Services Building
434 Monroe Street
Montgomery, Alabama 36130

205/834-1303

Hazardous Waste Program
Department of Environmental Conservation
Pouch O
Juneau, Alaska 99811

907/465-2666

Hazardous Waste Section
Bureau of Waste Control
Department of Health Services
1740 West Adams Street
Phoenix, Arizona 85007

602/255-1160

Air and Hazardous Materials Division
Department of Pollution Control and Ecology
8001 National Drive
Little Rock, Arkansas 72209

501/562-7444

Hazardous Waste Management Branch
Department of Health Services
714/744 P Street
Sacramento, California 95814

916/324-2428

Waste Management Division
State Department of Health
4210 E. 11th Avenue
Denver, Colorado 80222

303/320-8333

Hazardous Waste Management Section
Department of Environmental Protection
122 Washington Street
Hartford, Connecticut 06013

Telephone: (203) 566-5712

Solid Waste Management Branch
Department of Natural Resources and Environmental Control
P. O. Box 1401
Dover, Delaware 19901

302/736-4761

Division of Pesticides and Hazardous Materials
Department of Environmental Services
Government of the District of Columbia
5000 Overlook Avenue, S.W.
Washington, D.C. 20032-5397

Hazardous Waste Management Program
Department of Environmental Regulation
Twin Towers Office Building
2600 Blair Stone Rd.
Tallahassee, Florida 32301

904/488-0300

Industrial and Hazardous Waste Management Program
Environmental Protection Division
Department of Natural Resources
270 Washington Street, S.W.
Atlanta, Georgia 30334

404/656-2833

Environmental Protection and Health Services Division
State Department of Health
P. O. Box 3378
Honolulu, Hawaii 96801

808/548-6908

Hazardous Materials Bureau
Division of Environment
Department of Health and Welfare
Statehouse
Boise, Idaho 83720

208/334-4118 or 4064

Division of Land/Noise Pollution Control
Illinois Environmental Protection Agency
2200 Churchill Road
Springfield, Illinois 62706

217/782-6760

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* This listing was compiled from the HAZARDOUS WASTE REGULATORY GUIDE, published by J. J. Keller and Associates, Inc., Neenah, WI.

9 3 1 2 9 0 4 1 4 4 1

Hazardous Waste Management Branch
Indiana State Board of Health
1330 West Michigan Street
Indianapolis, Indiana 46206

317/633-0176

Air and Land Quality Division
Department of Environmental Quality
Henry A. Wallace Building
Des Moines, Iowa 50319

515/281-8927

Hazardous Waste Management Section
Bureau of Environmental Sanitation
Department of Health and Environment
Topeka, Kansas 66620

913/862-9360, Ext. 297

Division of Waste Management
Department for Natural Resources and Environmental Protection
Fort Boone Plaza, 18 Reilly Road
Frankfort, Kentucky 40601

502/564-6716

Hazardous Waste Management Division
Department of Natural Resources
P. O. Box 44066
Baton Rouge, Louisiana 70804

504/342-1227

Bureau of Oil & Hazardous Materials Control
Department of Environmental Protection
State House Station 17
Augusta, Maine 04333

207/289-2251

Hazardous Waste Division
Department of Health and Mental Hygiene
201 W. Preston Street
Baltimore, Maryland 21201

301/383-5734

Division of Hazardous Wastes
Department of Environmental Quality Engineering
One Winter Street
Boston, Massachusetts 02108

617/292-5630

Office of Hazardous Waste Management
Department of Natural Resources
P. O. Box 30038
Lansing, Michigan 48909

517/373-2730

Division of Solid and Hazardous Waste
Minnesota Pollution Control Agency
1935 West County Road B2
Roseville, Minnesota 55113

612/297-2705

Division of Solid Waste Management
Bureau of Pollution Control
Department of Natural Resources
P. O. Box 10385
Jackson, Mississippi 39209

601/961-5171

Hazardous Waste Management Section
Department of Natural Resources
P. O. Box 1368
Jefferson City, Missouri 65102

314/751-3241

Solid Waste Management Bureau
Department of Health and Environmental Sciences
Cogswell Building, Room A201
Helena, Montana 59620

406/449-2821

Water and Waste Management Division
Department of Environmental Control
Box 94877, Statenouse Station
Lincoln, Nebraska 68509

402/471-2186

Division of Environmental Protection
Department of Conservation and Natural Resources
201 S. Fall Street
Capitol Complex
Carson City, Nevada 89710

702/885-4670

Office of Waste Management
Bureau of Hazardous Waste Management
Department of Health and Welfare
Health & Welfare Building
Hazen Drive
Concord, New Hampshire 03301
603/271-4608

Division of Waste Management
Department of Environmental
Protection
CN 027
Trenton, New Jersey 08625

609/292-8341

Hazardous Waste Unit
Environmental Improvement Division
P. O. Box 968
Santa Fe, New Mexico 87503

505/827-5271

Division of Solid Waste
Department of Environmental
Conservation
50 Wolf Road
Albany, New York 12233

518/457-6603

Solid and Hazardous Waste Management
Branch
Department of Human Resources
P. O. Box 2091
Raleigh, North Carolina 27602

919/733-2178

Division of Environmental
Waste Management & Research
State Department of Health
1200 Missouri Avenue
Bismarck, North Dakota 58505

Ph: (701) 224-2366

Division of Hazardous Materials
Management
Ohio EPA
361 East Broad Street
Columbus, Ohio 43215

614/466-7220

Industrial Waste Division
State Department of Health
P. O. Box 53551
Oklahoma City, Oklahoma 73152

405/271-5338

Hazardous Waste Section
Solid Waste Division
Department of Environmental Quality
P. O. Box 1760
Portland, Oregon 97207

503/229-5913

Division of Hazardous Waste
Management
Department of Environmental
Resources
P. O. Box 2063
Harrisburg, Pennsylvania 17120

717/787-7381

Division of Air and Hazardous
Materials
Department of Environmental
Management
75 Davis Street
Providence, Rhode Island 02908

401/277-2797

Bureau of Solid and Hazardous
Waste Management
Department of Health and Environmental
Control
2600 Bull Street
Columbia, South Carolina 29201

803/758-5681

Office of Air Quality
and Solid Waste
Department of Water and Natural
Resources
Joe Foss Building, Room 217
Pierre, South Dakota 57501

605/773-3329

Division of Solid Waste Management
Department of Health
7th Floor TERRA Building
150 Ninth Avenue North
Nashville, Tennessee 37203

615/741-3424

Industrial Solid Waste Section
Texas Department of Water Resources
P. O. Box 13087
Capitol Station
Austin, Texas 78711

512/475-2041

Bureau of Hazardous Waste Management
Department of Health
P. O. Box 2500
Salt Lake City, Utah 84110
801/533-4145

Air and Solid Waste Programs
Agency of Environmental Conservation
Montpelier, Vermont 05602

802/828-3395

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Division of Solid and
Hazardous Waste Management
Department of Health
Richmond, Virginia 23219
804/786-5271

Hazardous Waste Section
Department of Ecology
Mail Stop PV-11
Olympia, Washington 98504

206/459-6305

Ground Water/Hazardous Waste Branch
Department of Natural Resources
1201 Greenbrier Street
Charleston, West Virginia 25311

304/348-5935

Hazardous Waste Management Section
Bureau of Solid Waste Management
Department of Natural Resources
P. O. Box 7921
Madison, Wisconsin 53707

608/267-0833

Solid Waste Management
Department of Environmental Quality
Hathaway Building
Cheyenne, Wyoming 82002

307/777-7752

Hazardous Waste Services Directory

Consultants and engineers with capabilities in landfill design are listed in the "Hazardous Waste Services Directory" published by J. J. Keller and Associates, Inc., Neenah, WI.

Information Sources/Types Pertinent to HWS Investigations

The following list, from Sisk (1981), names a variety of information sources and types potentially useful to HWS investigations.

SOURCES	TYPES/COMMENTS
1. EPA and State Environmental Office files for: RCRA permits and applications	
Waste Generators and Transporters	EPA Identification numbers Generator annual reports
TOSCA	May require special clearance for reviewer
NPDES permits and applications	Liquid waste types Treatment processes Production information
Uncontrolled waste disposal sites	
Spills of oil and hazardous materials	
Water supplies	Nearest water supply
Enforcement actions	
Surveillance reports	Problem history Previous findings
2. County or Regional Planning Agencies for Areawide Waste Treatment Mgmt. (CWA - Section 208 Agency)	Plans, concerns, and past problems
3. Other County offices	
Health Department	Problems, complaints, analytical results
Planning and zoning	Land use restrictions
Assessor	Plat maps and land owners
4. City offices	
Chamber of Commerce	Information and local industries incl. number of employees, principal products, and facility addresses
Clerk	
Engineer	Foundation and inspection reports Survey benchmark locations
Fire Department	History of fires and/or explosions at facility
Law Enforcement	Complaints and violations of local ordinances

Water and Sewer	Location of buried mains and lines
5. Company files and records	Confidential records require special handling and storage
6. Contractors	
Building	Local soils, geology, and shallow water levels
Soil exploration and foundation Water well drillers	Local soils, geology, hydrogeology, water levels, regulations, and equipment availability
7. Utility Companies Gas Electric Water Petroleum or Natural Gas Pipelines	Location of buried lines
8. U.S. Geological Survey	Technical geologic and hydrologic reports, maps, aerial photographs, and water monitoring data
9. Remote Sensing Imagery	Drainage patterns, land use, vegetation stress, historical land development, and geologic structure
10. Computer Data Bases	Wide variety of reference data and bibliographies
11. U.S. Department of Agriculture	Soil maps, types, physical characteristics, depths association, and uses
12. State Geological Surveys	Technical geologic and hydrologic reports, State geologic maps, and monitoring data
13. U.S. Department of Labor Occupational Safety and Health Administration (OSHA)	Processes Hazards Protective equipment needs
14. National Oceanic and Atmospheric Administration (NOAA)	Climatic data
15. National Ocean Survey Tidal Analysis Branch C232 Rockville, MD 20852 FTS: 443-8311	Tidal data; historic, recent, and projected

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