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Geotechnical Reduction Of Void Ratio In Low-Level Radioactive Waste Burial Sites: Treatment Alternatives

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R.A. Carlson
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Prepared for the United States
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Under Contract DE-AC06-77RL01030

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GEOTECHNICAL REDUCTION OF VOID RATIO IN LOW-LEVEL RADIOACTIVE WASTE BURIAL SITES: TREATMENT ALTERNATIVES

S. J. Phillips
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ABSTRACT

A substantial quantity of low-level radioactive and hazardous wastes has been interred in shallow land burial structures throughout the United States. Many of these structures (trenches, pits, and landfills) may require further stabilization. Some surface feature manifestations such as large cracks, basins, and cave-ins are caused by voids filling, and by physicochemical degradation and solubilization of the buried wastes which could result in the release of contamination. The surface features represent a potential for increased contamination transport to the biosphere via water, air, biologic, and direct pathways.

Engineering alternatives for the reduction of buried waste and matrix materials voids are identified and discussed. As a guideline, a reduction of the voids within the waste to 80% or more of maximum relative dry density (a measure of in situ voids within the waste) is proposed. The advantages, disadvantages, and costs of each alternative are evaluated.

Falling mass and pile driving engineering alternatives were selected for further development.

CONTENTS

Introduction. 1

Criterion and Guideline 5

Alternatives. 6
Alternative I: Rollers/Eccentric Compactors 6
Alternative II: Vibroflotation. 9
Alternative III: Explosives 11
Alternative IV: Post Loading. 13
Alternative V: Falling Mass 13
Alternative VI: Pile Driving. 15

Costs 20

Applications. 21

Future Efforts. 22

Conclusions 22

References. 24

FIGURES:
1. Void Filling. 2
2. Cave-In 3
3. Tension Cracking. 4
4. Roller Alternative. 8
5. Vibroflotation Alternative. 10
6. Explosives Alternative. 12
7. Postloading Alternative 14
8. Falling Mass Alternative. 16
9. Pile Driving (Piles Retrieved) Alternative. 18
10. Pile Driving (Piles Remain) Alternative 19

TABLE:
1. Treatment Alternatives Costs. 21

INTRODUCTION

Numerous operational and postoperational (retired) low-level radioactive waste sites[a] exist within the United States. Subsidence of buried waste material and overburden within burial structures[b] at these radioactive waste disposal sites is potentially a problem which may result in contaminant transport. Numerous radioactive waste burial structures have, to some degree, been geotechnically unstable as evidenced by subsidence for more than three decades.(1-8) Subsidence results from general settling and filling of voids within the waste site. It is caused by numerous geotechnical[c] processes which induce changes in stress-strain relationships within the burial structure, and solubilization and degradation of the waste form. These processes are interrelated and act simultaneously over time.

Many nuclear waste disposal sites, both commercial and defense, have experienced subsidence problems with the overburden of waste disposal structures. However, nuclear waste disposal sites currently have radiological control methods and procedures to adequately contain waste materials from entering controlled areas at unacceptable concentrations. Continuous maintenance of these sites can be costly, and the potential occupational and public risk of radionuclide or contaminant transport to the biosphere may be increased. This report is intended to discuss engineering techniques potentially useful for long-term stabilization of waste disposal sites to augment current remedial action activities where loss of institutional control is assumed.

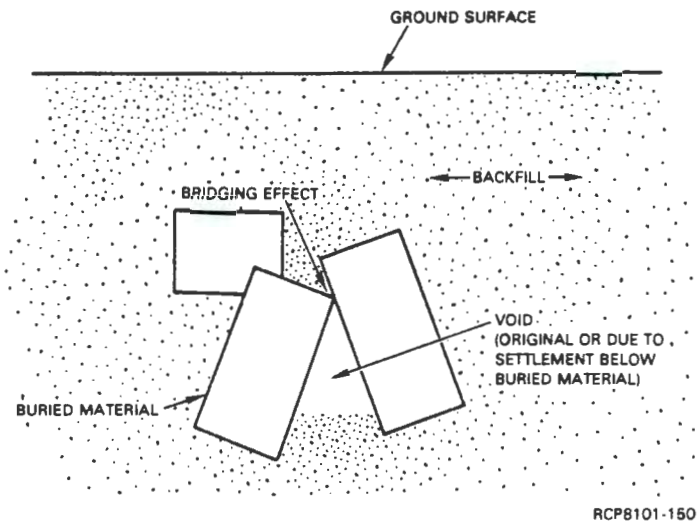
Figures 1 through 3 illustrate typical surface manifestations of subsidence occurring at waste disposal sites. These figures depict void filling, cave-ins, tension cracking, basining, infiltration, and biomass growth, all of which can result in radiation waste exposure or release of contaminants to the biosphere.

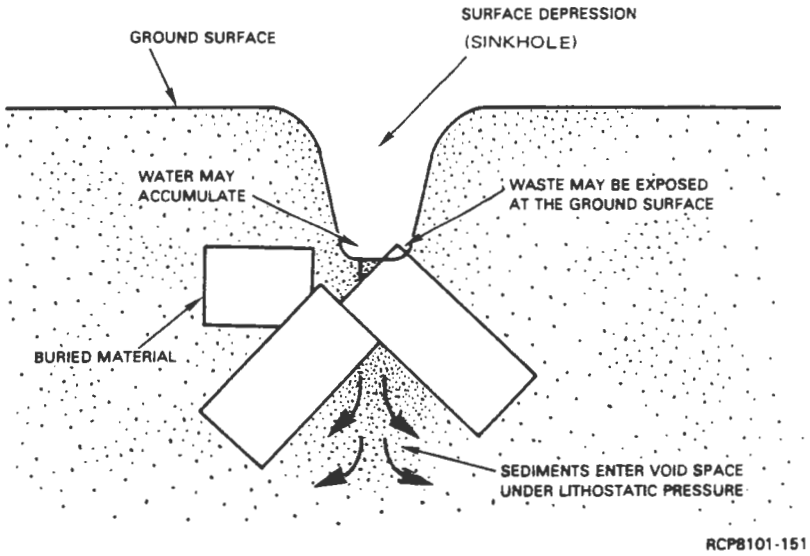
---

[a]Burial Site: A general area, i.e., burial ground, containing buried structures. May also contain support facilities when operational.

[b]Burial Structure: A trench, pit or landfill within a burial site.

[c]Geotechnical: Of or related to geologic media behavior.





Generalized illustration of the effect of void filling in waste burial sites showing simple void filling. Additional mechanisms including waste package collapse and waste form solubilization will result in the same subsidence manifestations.

FIGURE 1. Void Filling.

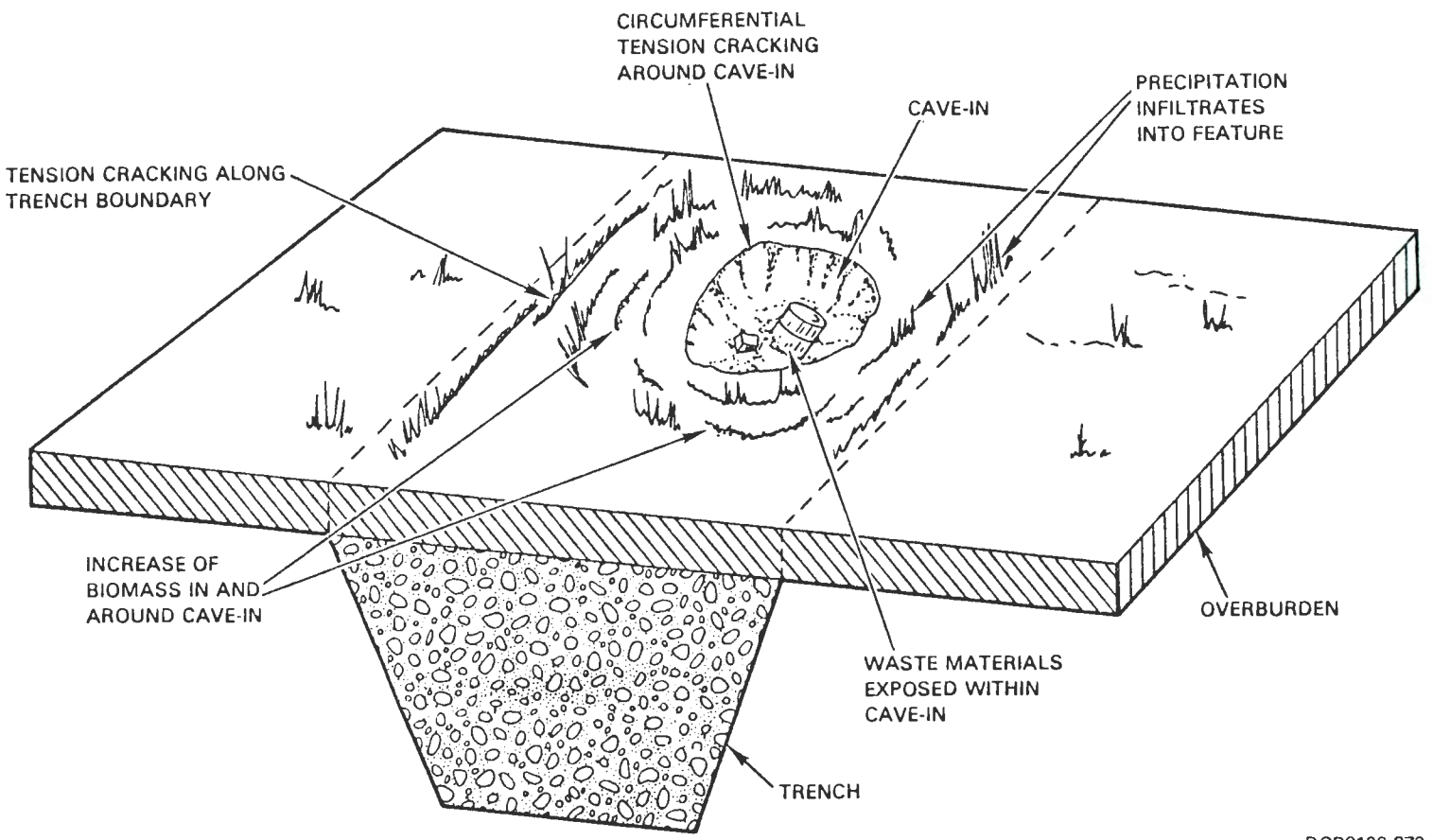


FIGURE 2. Illustration of Subsidence Cave-In. Cave-ins can directly expose waste materials, induce plant growth, and increase infiltration. Animal intrusions can also be found within these features. Cave-ins approximately 5 m in diameter and 3 m in depth can occur. Tension cracks also occur circumferentially around this subsidence feature.

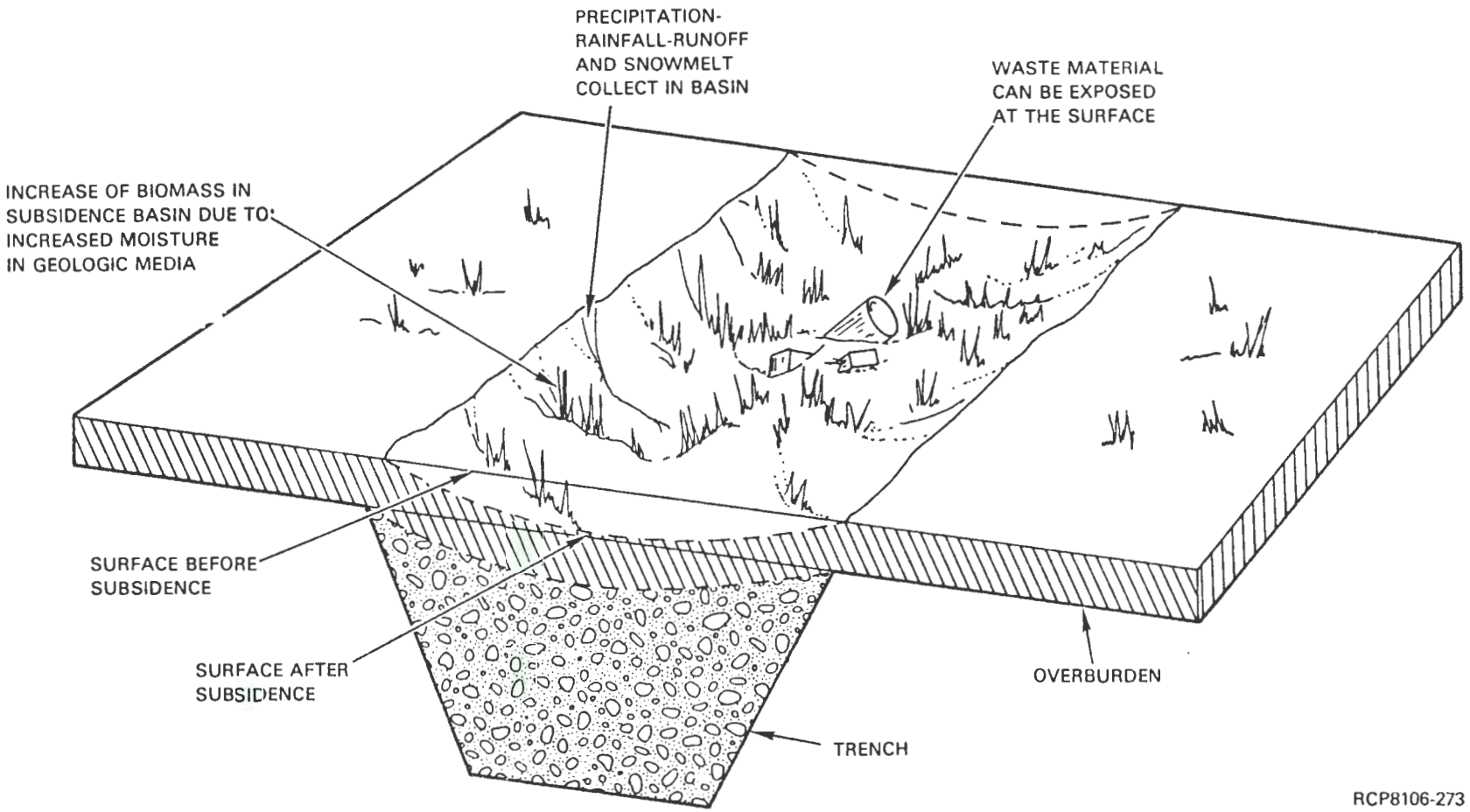


FIGURE 3. Illustration of Subsidence Basining. Basining can occur over an entire burial structure or result from coalescence of cave-ins. Precipitation (rainfall and runoff) can enter these basins and potentially increase the flow through the burial structure resulting in a greater potential for contaminant transport.

This report delineates several examples of surface subsidence manifestations at waste burial structures. A criterion and guideline are proposed for the reduction of potential subsidence. Engineering alternatives to control subsidence and water infiltration into burial structures are identified and evaluated for their effectiveness, disadvantages, and costs. Future efforts to test and demonstrate subsidence control and possible remedial actions are also discussed.

CRITERION AND GUIDELINE

In order to reduce actual and future potential subsidence of buried waste sites and resultant contaminant transport to the biosphere, it may be prudent to propose a criterion and guideline which site operators and administrators should strive to achieve. The criterion and guideline are delineated below.

Criterion: "The void ratio[a] of buried waste and matrix materials will be minimized such that actual and potential contaminant transport and exposure are reduced to acceptable limits."

Guideline: "The void ratio of buried waste and matrix material within a burial structure should be reduced to achieve 80% or more of maximum relative dry density[b] by use of operational and postoperational compaction alternatives."

Void ratio reduction by engineering techniques in waste burial structures has not been adequately demonstrated. Only after successful demonstration should the proposed criterion and guideline be considered for implementation into low-level radioactive waste site design and operational guidance.

---

[a]Void Ratio: The volume of voids to volume of solids.

[b]Maximum Relative Dry Density: A measure of the in situ degree of compaction.

Several field and laboratory tests have been developed that are related to the evaluation of void ratio reduction, as established by the American Society for Testing and Materials (ASTM), American National Standards Institute (ANSI), and the American Association of State Highway Transportation Officials (AASHTO). These guideline tests can be used to help experimentally determine and achieve the maximum relative dry density guideline proposed.[9-16]

ALTERNATIVES

Several geotechnical alternatives for treating burial structures to reduce the void ratio have been identified and are discussed herein. These alternatives, as a point of commonality, transmit a load through the buried waste and matrix materials to subsequently impart compaction. The load is transmitted through the materials to impart a stress distribution which is primarily a function of the geotechnical treatment used. The load produces stress in all directions, a normal (compression component) stress is produced perpendicular to the load plane, a tangential (shearing component) stress is produced in the same plane as the applied load. The normal stress imparts compression and subsequent void volume reduction. Load stresses and stress-strain properties of the buried geologic media[a] and/or waste are used to determine displacement of the buried materials at any point in the burial structure. The identified alternatives typically impart both vertical and horizontal stresses to produce optimum compaction. These alternatives are discussed below.

ALTERNATIVE I: ROLLERS/ECCENTRIC COMPACTORS

Rollers have been successfully used to compact geologic media for stabilization purposes. Typically, these units are used for stabilizing

---

[a]Geologic Media: Natural soil, regolith, or rock material typically used as foundation materials, backfill, overburden, or burial structure fill.

highway and building foundations. These units are also proposed for use at operational waste burial sites. Rollers impart a vertical pressure and can be used on either cohesive[a] or noncohesive[b] geologic media.

Cohesive materials may be compacted by sheepsfoot rollers. These rollers impart a high static pressure which varies from 2 to 20 Kg cm^{-2} over a small surface area. Greater than 90% of maximum relative dry density can be achieved in clay materials up to about 20 cm layers with 5 to 10 passes over the surface. The configuration of sheepsfoot rollers can vary depending on materials to be stabilized, the site morphology, and the support equipment available. These units can be used in singular or in tandem arrangement.

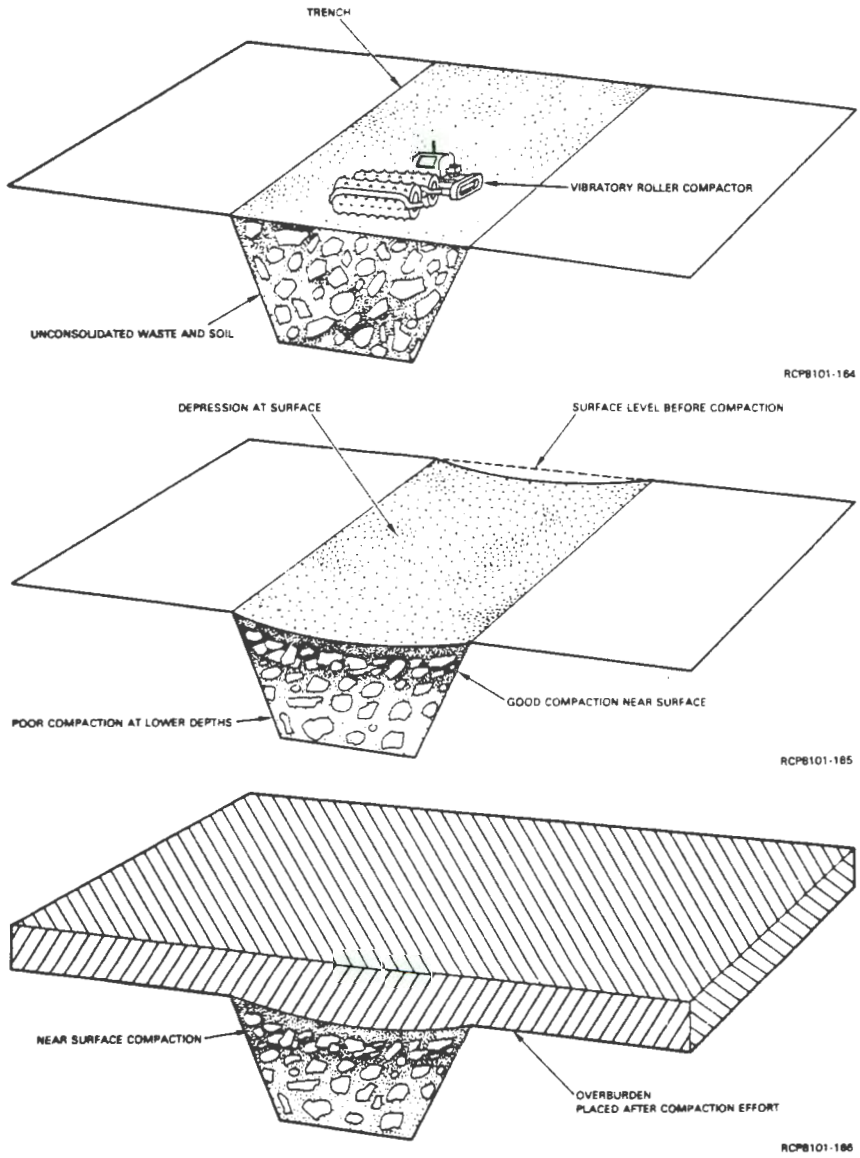
Low cohesive or noncohesive materials are often compacted by drum or pneumatic-tired rollers. These units are used for geologic media types including: gravels, sands, and sandy silts. Drum rollers are often capable of compaction of greater than 90% of maximum relative dry density within layers in excess of 40 cm in depth with 5 to 9 repetitive passes. Pressure exerted by these rollers may be on the order of 10 Kg cm^{-2}. Pneumatic-tired rollers are capable of achieving greater than 95% of maximum relative dry density after approximately five passes. These units are used to compact geologic media in lifts (layers) up to 45 cm in thickness. Pressure imparted by these rollers range from 2 to 10 Kg cm^{-2}.

Vibrating shoes or eccentric vibration compaction devices can also be used to consolidate geologic media. These can either be used as standalone devices or coupled with drum or pneumatic-tired devices. They are capable of compacting noncohesive geologic media to greater than 95% of maximum relative dry density to depths in excess of 3.0 m. Figure 4 illustrates the compaction by vibrating rollers.

---

[a]Cohesive Soil: Soil grains which upon wetting and subsequent drying adhere and require a force to separate them in the dry state.

[b]Noncohesive or Cohesionless: Soil grains fall apart after drying and only adhere when wet due to surface tension forces.



Surface compaction using rollers. This alternative may not be adequate to effect void filling at depth. Additions of water are also often required to achieve adequate void ratio reduction. The illustration shows (1) use of rollers, (2) their effect before implacement of overburden, and (3) the resultant burial structure after overburden implacement.

FIGURE 4. Roller Alternative.

These devices can only impart effective consolidation if the water content of the geologic media is within an acceptable range, i.e. approximately the optimum moisture content. The optimum moisture content is the required water content (%) which will result in the maximum relative dry density for a particular compaction method. Thus, the moisture content must often be controlled when rolling. The use of water and poor void ratio reduction are disadvantages for use of these devices at waste disposal sites. However, an advantage to using rollers is their low operational costs.

ALTERNATIVE II: VIBROFLOTATION

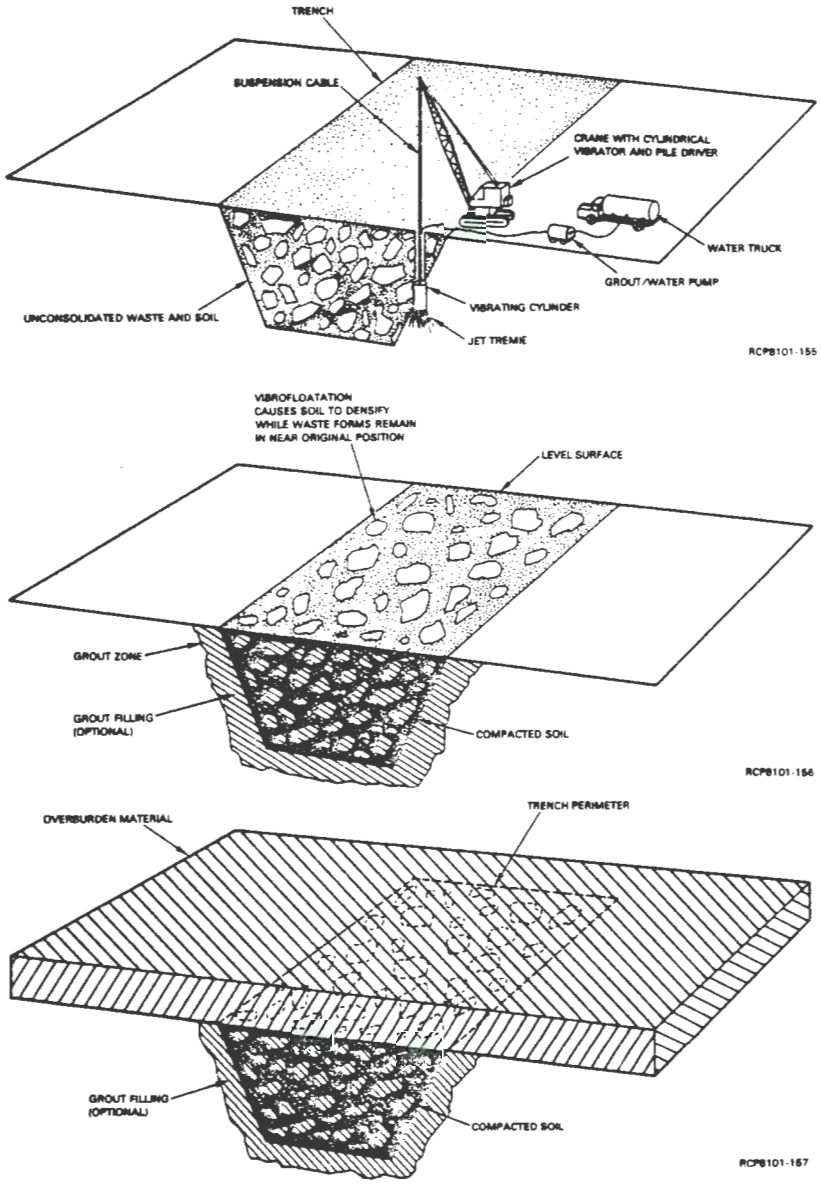
Vibroflotation is a variation of pile driving methods utilizing a jet-tremie[a] dynamically driven and withdrawn from the substrate. Vibroflotation is currently used to compact foundation materials via liquefaction[b] processes. This technique is used for noncohesive materials, typically sands and gravels.

The vibroflotation technique uses an eccentric weight inside of a large cylinder which imparts a lateral centrifugal force into the buried waste and matrix material. The cylinder typically is on the order of 50 cm in diameter to 3 m in length with a vibratory frequency of 1×10^5 Hz. Lateral forces imparted to the waste from the cylinder can range typically from 1.0×10^1 to 1.0×10^2 M Kgf. Water is injected through the top and bottom of the cylinder at a rate of about 6 L sec^{-1} at a pressure of about 6 Kg cm^{-2}. The water jet-tremie is forced into the substrate to a maximum depth by vertical pressure. The buried material is typically compacted during withdrawal of the jet-tremie. Compaction is usually adequate to a radial distance of 2.5 m from the well annulus. The degree of compaction can be on the order of 70% maximum relative dry density for most sand materials. Figure 5 is an illustration of compaction by vibroflotation.

---

[a]Jet-tremie: A cylindrical vibrating device that injects water into the site to loosen the waste matrix material.

[b]Liquefaction: Liquifying the geologic media by cyclic or dynamic loading that results in a loss of geologic media strength.



Vibroflotation water injection techniques in a burial structure. This alternative effects liquefaction of the waste matrix material which in turn results in void ratio reduction. Grout injection is often used which decreases waste interstitial void volume and forms a barrier to radionuclide transport. The illustration shows (1) injection of a jet-tremie into the burial structure, (2) the result of grout injection before implacement of overburden, and (3) the resultant burial structure after grouting and overburden implacement.

FIGURE 5. Vibroflotation Alternative.

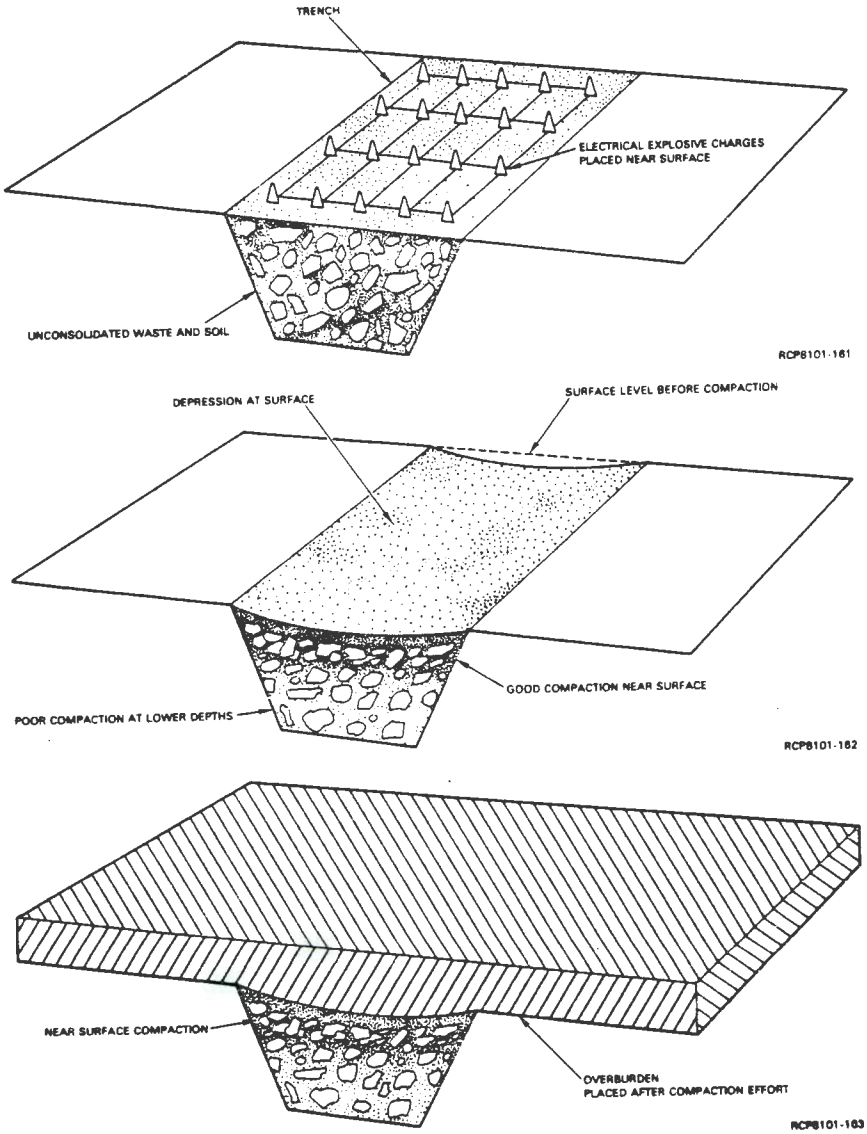
Vibroflotation has been used for injection of grouting agents. This may have application for waste site stabilization. A logical extension of this alternative is injection of grouting agents into the waste matrix during withdrawal. This reduces the relative void ratio (filling of interstitial voids) in that the primary waste voids are filled leaving only the voids within the grout material. Application to buried waste sites has not been successfully demonstrated. Water injection and high cost are disadvantages of this technique.

ALTERNATIVE III: EXPLOSIVES

Foundation materials in a few instances have been compacted by detonating explosive charges implaced within or on the ground surface. This method is typically used to initiate liquefaction of sands.

The use of explosives for compaction is most effective in noncohesive geologic media. The maximum relative dry density of geologic media can be increased to 60% by this technique. Blasting typically involves: (1) placement of charges within vessels near the ground surface or directly on the ground surface and (2) controlled detonation (vertical and lateral detonation such that the explosive force is contained below ground level) of the explosive charges. Single detonations may impart a vertical force into the burial structure typically between 1.0×10^2 to 1.0×10^4 M Kgf. Repeating detonations are typically more effective than single detonations. The effective radius of compaction may be on the order of 5 m. Ground settlement changes on the order of 0.5 m to 1.0 m are achievable in noncohesive geologic media. Decreases in hydraulic conductivity of the substrate by a factor of four are also possible for noncohesive materials. Relative location of the explosive charges and their effects are shown in Figure 6.

The blasting of buried material has a number of disadvantages including: (1) the substrate must be near saturation in order to achieve maximum void ratio reduction, (2) blasting in some instances may increase the void ratio around the point of detonation, (3) buildings in the vicinity may be damaged by the shock wave propagated through the site, and (4) may increase the potential for release of contaminants to the biosphere.



Use of explosives for reduction of voids in waste burial structures. This alternative may be potentially effective on some waste forms. Poor void ratio reduction at depth may be expected. The illustration shows (1) the configuration of surface explosives (explosive arrays with depth may also be used), (2) the result of surface detonation of explosives compacting the waste and waste matrix, and (3) the resultant burial structure after overburden implacement.

FIGURE 6. Explosives Alternative.

Studies of the effectiveness of the explosive technique on typical buried waste have not been conducted. Extensive field testing and development of this technique would be required prior to use for stabilizing waste burial sites. Public acceptance of this technique for compaction of burial structures may be a major concern.

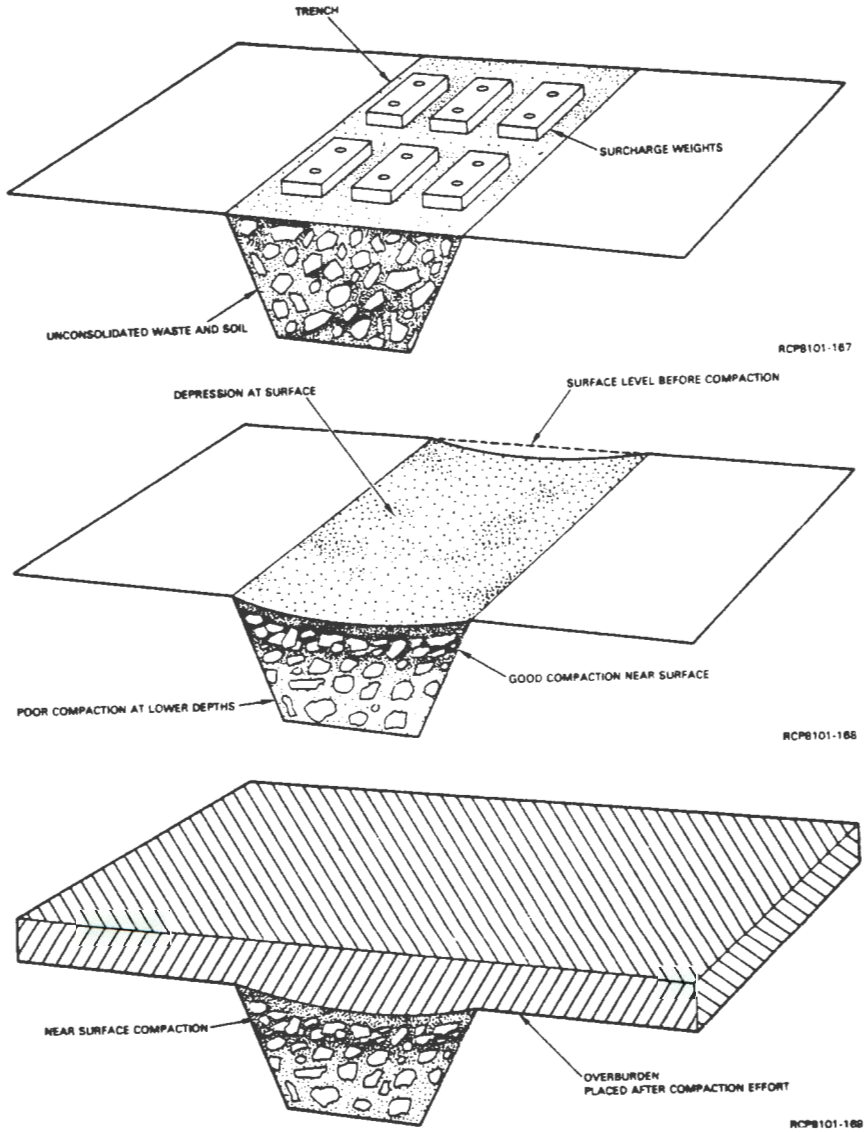
ALTERNATIVE IV: POST LOADING

Static post loading of burial sites for void ratio reduction and successive site stabilization is a variation of surcharging or preloading of foundation materials. Surcharging is a common preconstruction technique for compaction of geologic media which will support building structures. Post loading involves placement of a static load of sufficient mass per unit area over a burial structure to consolidate the burial materials and interstitial geologic media to an acceptable void ratio. This mass may consist of materials such as geologic fill or large concrete blocks. The vertical pressure imparted on the burial structure by post loading may range between 5 to 10 Kg cm^{-2}. The rate of settlement may be theoretically determined for most applications. However, the rate is typically determined for saturated noncohesive or moderately cohesive geologic media where simultaneous consolidation and draining occurs. Static post loading has not been found effective for most partially saturated geologic media. As with several other alternatives discussed, water application may be required in order to use this technique. Illustrations of surcharge loading burial sites are shown in Figure 7.

If the groundwater table is near the bottom of the burial structure, post loading may increase the positive pore pressure. This may cause the water table to rise into the burial structure. Thus, post loading where a shallow water table exists is not advisable. The costs of this technique are moderate with poor void ratio reduction with depth.

ALTERNATIVE V: FALLING MASS

Soil materials may be compacted using a falling mass. This technique has been successfully demonstrated on cohesive and noncohesive foundation materials which support small to moderate loads. This technique has been used to compact sanitary landfill materials.



Surface compaction using static post loading. This technique is similar to surcharging in foundation materials compaction. This alternative may not be adequate to reduce void ratios in numerous waste forms at depth. In addition, long-term operations may be required. The illustration shows (1) post loading of large masses, e.g., concrete over the buried waste, (2) the effect of shallow compaction before overburden implacement, and (3) the resultant burial structure after overburden implacement.

FIGURE 7. Postloading Alternative.

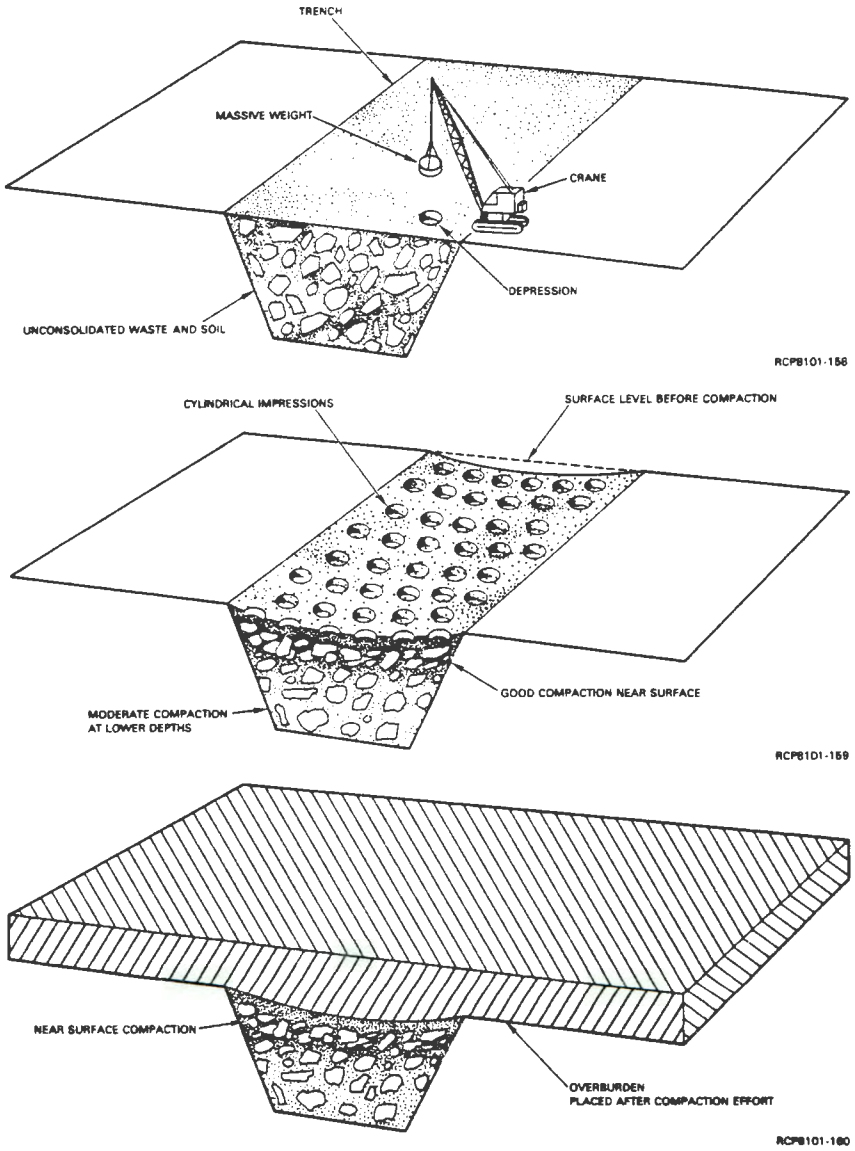
A falling mass striking the ground surface compacts the underlying material through shock waves of various frequencies. The amount of void ratio reduction is increased as the shock wave frequency approaches the resonant frequency of the underlying material. Void ratio reduction occurs when particulate materials are reorientated into high density packing configurations. Compaction using a falling mass, illustrated in Figure 8, is a function of the media, the shape and mass of the falling object, the drop height, and the number of drop repetitions. Compaction of foundation materials (loose, noncohesive) can be effected up to depths of 20 m using repetitive drops of mass of about 20 metric tons. The falling mass can impart from 1.0×10^3 to 1.0×10^6 M Kgf to the ground surface on impact depending on the aforementioned variables. Ground surface elevation changes up to 3 m can also be realized. The falling mass causes a cratering of the ground surface. The craters are leveled and compacted in thin lifts by conventional rolling methods.

Shock waves of significant amplitude may damage buildings or structures in the vicinity of the burial structure being compacted, a possible disadvantage of this technique. This technique requires sufficient overburden such that the waste will not be exposed upon impact of the falling mass. This technique will also cause increased pore pressure in the geologic media underlying the burial structure possibly causing a transient short-term rise in the ground water table. If the distance between the lowest depth of the burial structure and the ambient water table is small, use of this technique would not be advisable.

This method may not be amenable to stabilizing some cohesive geologic media materials. Some buried waste may also have physical properties which may not be compatible with this alternative. Moderate to good compaction with depth can be achieved with this technique at a low cost.

ALTERNATIVE VI: PILE DRIVING

Pile driving is an effective technique used to consolidate cohesive and noncohesive geologic media under saturated and partially saturated conditions. In addition, this technique has proved effective for post-operational compaction of landfill materials.



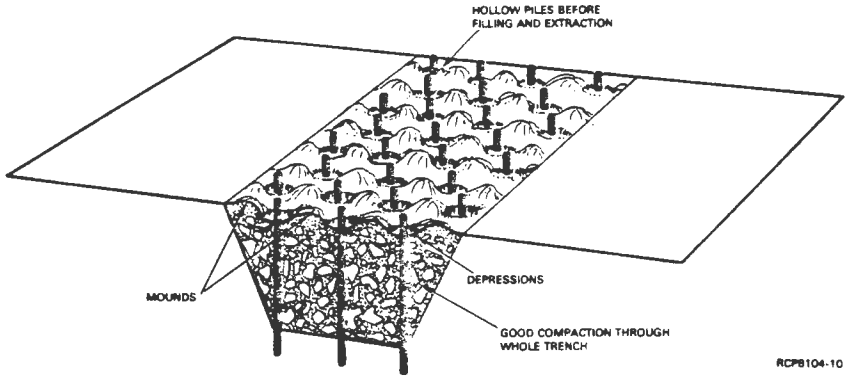
Waste compaction using a falling mass technique. This alternative has been selected for field testing. A mass of ∿20 metric tons is used to impart compaction. Craters are formed on the surface and overburden lifts are implaced in the craters after several repetitions. Good to moderate void ratio reduction with depth is possible. The illustration shows (1) use of the falling mass via crane operation, (2) cratering and void ratio reduction of the buried material, (3) implacement of overburden material over the compacted material.

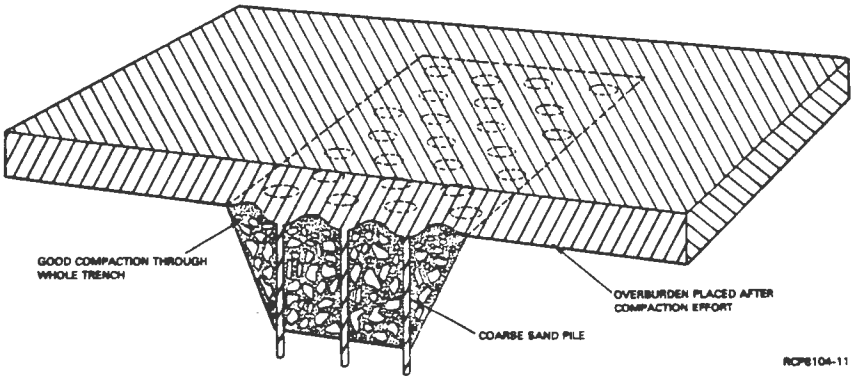
FIGURE 8. Falling Mass Alternative.

Reduction of void ratio via pile implacement is caused by vibration of the buried waste and matrix material media through which the pile is driven and volumetric displacement in proportion to the pile volume. Pile driving for the purpose of void ratio reduction consists of the following general procedures: (1) driving a vertical cylindrical casing with a detachable drive shoe into the material to be compacted and (2) withdrawal of the casing and simultaneous backfilling. Backfilling can be completed by placing, e.g., (1) coarse sand within the well annulus and pile casing during withdrawal or (2) fine textured material (clay) within the well annulus and coarse sand within the pile casing during withdrawal. The purpose of the coarse sand backfill is to create vertical drains causing a preferential water pathway through the compacted waste. Compaction is readily apparent and typically extends over 3 to 5 pile diameters horizontally and 3 to 6 diameters below the pile. In excess of 80% maximum relative dry density may be realized using this technique. The forces imparted by the pile may range between 1.0×10^2 and 1.0×10^4 M Kgf. Auxiliary vibratory hammers used in conjunction with the pile driver may augment compaction, but this has not been demonstrated. Pile driving creating vertical sand drains is illustrated in Figure 9.

The pile driving technique is used for void ratio reduction coupled with geohydrologic partially saturated water flux control. Potential radiation exposure during pile withdrawal is a risk. However, minimization of exposure has been demonstrated on withdrawal of well casings at numerous sites. Pile driving is the best technique for void ratio reduction with depth technique.

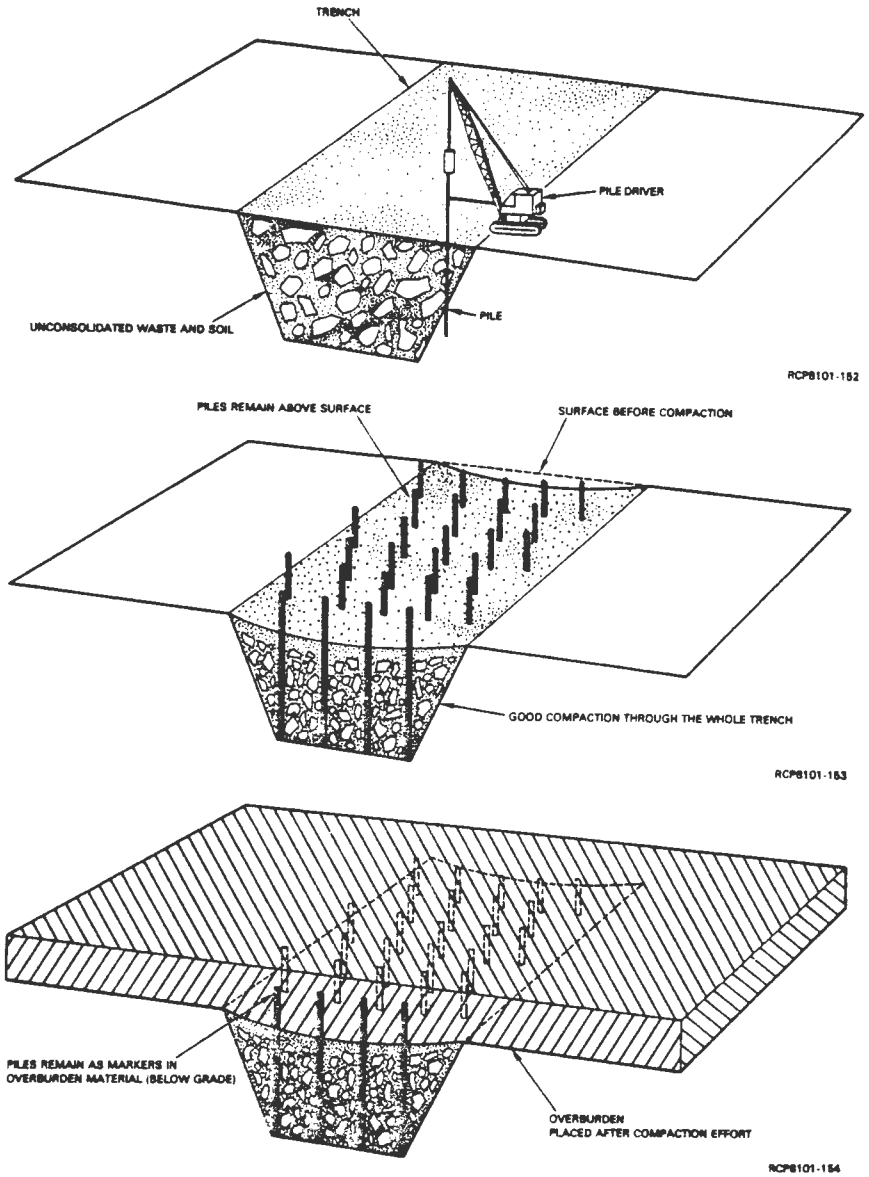
An optional technique of pile driving involves leaving permanent piles in the site. The piles should consist of synthetic or naturally durable materials which will slowly deteriorate over the hazardous life of the site. The piles are driven such that a vertical extension remains above grade. Overburden is then placed over the piles. Illustrations of this pile driving technique are shown in Figure 10. If the site were to undergo excessive erosion the piles would be exposed at the ground surface. This





Pile driving using retrievable piles for dynamic consolidation and reduction of void ratio. Pile driving, retrieval, and backfilling of piles has been selected alternative for field testing. This alternative utilizes the fact that water infiltration through the overburden will preferentially flow through the backfilled piles, i.e., reduce the potential for groundwater contamination. This will reduce the waste/water contact time and subsequently reduce waste transport from the burial structure. The piles can be backfilled with clay/sand in a coaxial configuration or with coarse sand and the piles removed. The illustration shows (1) implacement of piles to reduce waste materials void volume and (2) the resultant burial structure with vertical drains extending through the waste into the substrate.

FIGURE 9. Pile driving (Piles Retrieved) Alternative.



Compaction using pile driving for dynamic consolidation. Pile driving has been selected for field testing. Pile driving reduces void ratio laterally and vertically. This alternative technique involves leaving piles in place as markers for intrusion. The illustration shows (1) implacement of piles with guideline pile driving equipment, (2) compaction of the waste materials at depth throughout the burial structure, and (3) the resultant burial structure after overburden is placed over the trench.

FIGURE 10. Pile Driving (Piles Remain) Alternative.

would indicate to the site operator or custodian that a potential hazard exists. Thus, the operator or custodian could initiate an action before loss of waste confinement occurs. The cost of this option is more than removing piles, but the potential for radiological exposure is reduced.

The pile driving techniques may have several disadvantages depending on the burial structure design. Burial trenches in humid regions may be designed with a clay liner and a drain system. Piles would breach trench liners and drains. However, piles with sand drains would negate the need for liners and similar barriers. As with the falling mass and explosive alternatives, shock waves may be propagated through the burial structure and surrounding geologic media to nearby buildings causing structural damage.

COSTS

The cost to reduce the void ratio of materials within burial structures varies with such factors as: (1) treatment alternative selected, (2) wasteform, (3) burial structure shape and size, (4) number of burial structures per site, (5) occupational exposure limits. Cost estimates for the geotechnical engineering alternatives will require a rigorous assessment of the above factors. Preliminary costs for each alternative have been determined (Table 1). For cost estimating purposes a hypothetical burial site consisting of 10 burial structures (trenches) was used. The dimensions of each structure were 5 x 10 x 100 m with respect to depth, width, and length. The costs range between $30 thousand to $4.1 million per site. The falling mass and pile driving alternatives (those alternatives with the highest probability of success) are low to intermediate in overall cost.

TABLE 1. Treatment Alternatives Costs.

Treatment Alternative	Preliminary Cost Estimate Range per Hypothetical Burial Site (x $1000s)
Rollers	30 - 40
Vibroflotation	
- w/o grout	260 - 330
- w grout	2,730 - 4,100
Explosives*	
- w/o surface plates	120 - 150
- w surface plates	960 - 1,200
Post Loading	650 - 910
Falling Mass*	90 - 120
Pile Driving*	
- piles in place	820 - 1,020
- piles removed	230 - 290

*Assume 2.5 m centers.

APPLICATIONS

The falling mass and pile driving control alternatives are planned for field testing at an uncontaminated and subsequently at a contaminated postoperational burial structures on the Hanford Site, Richland, Washington. Field testing will include monitoring of compaction parameters including such factors as: (1) shock wave propagation and magnitude, (2) triaxial stress/strain, (3) settlement, (4) density, (5) volumetric moisture (negative pore pressure) content, and (6) mass volume change. Upon successful field testing and actual demonstration of these alternatives they may be applied to other nuclear waste burial sites. These alternatives, as currently envisioned, will be generically applicable at both humid and arid sites where waste materials exist under partially saturated or saturated groundwater conditions.

FUTURE EFFORTS

Geotechnical alternatives to reduce the void ratio of buried waste and matrix materials have been evaluated on a preliminary basis. The falling mass and pile driving alternatives are the most feasible techniques for testing in situ. Laboratory and field investigations are planned in order to evaluate the effectiveness of these alternative treatments. Laboratory geologic media mechanics techniques to determine stress-strain relationships of geologic media and selected waste forms under a range of physical static and dynamic conditions will be used. Field testing under controlled conditions will be conducted to evaluate their applicability and effectiveness. Subsequently, demonstration of the developed techniques at actual waste disposal sites is planned. Simulation and prediction of coupled subsidence and partially saturated moisture migration using empirical and numerical computer codes will be completed. Dissemination of information by technical publications will be completed after field demonstration of the alternatives.

CONCLUSIONS

Radioactive waste burial structures may subside over time due to in situ interstitial void filling and waste physicochemical solubilization and degradation. As a result: (1) excessive meteoric water may enter the burial structure, (2) biologic (flora and fauna) intrusion and uptake may occur (3) entrainment and transport in the atmosphere may occur, and (4) direct exposure to the public or occupational workers may result at the location of the subsidence feature. Subsidence is thought to be the primary cause of loss of confinement and transport of contaminants at numerous burial sites.

The void ratio of materials within burial structures may be intentionally reduced using geotechnical techniques. Reduction of void ratio will mitigate the potential for subsidence and resultant exposure.

Falling mass and pile driving techniques are suggested as viable alternatives for field testing and demonstration. A criterion to minimize the void ratio and a guideline to reduce the void ratio to 80% of maximum relative dry density in burial structures are proposed.

Further development testing of geotechnical alternatives to reduce the void ratio in burial structures is ongoing. Demonstration of alternatives potentially capable of maximum void ratio reduction with depth is proposed for 1982.

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