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Prediction/Mitigation of Subsidence Damage to Hazardous Waste Landfill Covers

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PREDICTION/MITIGATION OF SUBSIDENCE DAMAGE TO HAZARDOUS WASTE LANDFILL COVERS

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of the State and local governments, and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes the causes and effects, prediction methods, and technologies that may be applied for the prevention of subsidence in hazardous waste landfills. The information should be of assistance to those involved in evaluating landfill permit applications. The goal is to help prevent damage to, and resulting leaks through, landfill covers caused by subsidence-induced stresses.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

Characteristics of Resource Conservation and Recovery Act hazardous waste landfills and of landfilled hazardous wastes have been described to permit development of models and other analytical techniques for predicting, reducing, and preventing landfill settlement and related cover damage by subsidence. Landfill settlement results from the consolidation and secondary compression of the waste mass and from the collapse of voids in the fill and of containers and other debris by corrosion, oxidation, combustion or biochemical decay. Landfills may be described as containing a single type of waste, a monofill, or as containing different types of wastes heterogeneously such as bulk, in containers, and as debris. Differential settlement across short distances is more threatening than relatively uniform settlement across longer distances. The potential for differential settlement is considered to be greater in heterogeneous landfills than in monofills. Settlement of bulk waste landfills is relatively predictable and is expected to be essentially complete before final closure if adequate provisions are made for internal drainage of fluids. Settlement of landfills with containerized wastes is more difficult to predict because the containerized wastes may remain relatively undeformed until the containers degrade and collapse. The void space around and in containers can be a major contributor to total postclosure settlement. Accordingly, steps should be taken to minimize the void component of settlement by backfilling voids during waste placement or by eliminating the disposal of drums and other waste containers. Settlement of some landfills can be predicted by analyzing the deformation of a central column consisting of layers of wastes and intermediate cover material. Bulk waste (monofill) landfills can be analyzed by consolidation theory. The potential for differential settlement can be analyzed by treating the final cover as a beam and determining the tensile stresses that develop in the cover layers. Differential settlement can also be analyzed by determining the deformation of two or more central columns. Damage to the final cover by differential settlement can be minimized by compacting wastes during placement, by eliminating void space within the landfill, by stabilizing liquids before placement, and by adjusting cover component specifications to minimize the effects of tensile strain.

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The study was conducted and the report prepared by Messrs. Paul A. Gilbert, Soil Mechanics Division and William L. Murphy, Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES). Direct supervision was provided by Mr. James H. May, Chief, Site Characterization Unit, Engineering Geology Applications Group, EGRMD; Dr. Don C. Banks, Chief, EGRMD; and Dr. William F. Marcuson III, Chief, GL. Mr. Robert P. Hartley was EPA Project Officer for the study and provided guidance and assistance during the investigation.

Director of WES during the initial study was COL Allen F. Grum, USA. Commander and Director of the WES during the study and preparation of the report was COL Dwayne G. Lee, CE. Technical Director was Dr. Robert W. Whalin.

SECTION 1

INTRODUCTION

BACKGROUND

Section 3004 of the Resource Conservation and Recovery Act (RCRA) of 1976 requires the Administrator of Environmental Protection Agency (EPA) to establish standards applicable to owners and operators of hazardous waste treatment, storage, and disposal (TSD) facilities. Among the standards are requirements for "treatment, storage, or disposal of all such waste received by the facility pursuant to such operating methods, techniques, and practices as may be satisfactory to the Administrator." The implementing regulations for landfill covers are found in 40 CFR 264.310, "Closure and postclosure care," which states that the final cover must be designed and constructed to (1) provide long-term minimization of migration of fluids 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; and (5) have a permeability less than or equal to the permeability of any bottom liner system or natural soils present.

Monitoring and maintenance, including necessary cover repairs, are also required throughout the postclosure period. The postclosure period is designated in 40 CFR 264.117 as 30 years after completion of closure.

EPA recognizes the need to provide guidance in implementing the cover requirements. This document addresses the fourth requirement listed above regarding settlement and cover subsidence.

PURPOSE

This report presents technical guidance directed at predicting, reducing, and preventing landfill settlement and related cover damaged by subsidence. The report is intended to be used by regulatory personnel and by operators of hazardous waste landfills.

SCOPE

The information in this report pertains to hazardous waste landfills designed, constructed, and operated within the United States under the RCRA regulations. Landfills constructed and capped before the passage of RCRA in 1976 may not meet RCRA's relatively stringent waste placement, liquid waste limitations, liner specifications, and leachate collection and control requirements, and thus may not be amenable to the analytical, construction, and remedial guidance presented in this report.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Hazardous waste landfills meeting RCRA requirements have physical characteristics that influence their potential for settlement and subsidence. Attention to those characteristics can minimize postclosure subsidence damage.

Data on physical properties of real and simulated hazardous waste are available to assist the landfill operator or permitting agency in assessing long- and short-term settlement potential.

Landfill subsidence results from primary consolidation and secondary compression of the waste mass, and from collapse of voids or cavities in the fill and around containers by corrosion, oxidation, combustion, or biochemical decay of landfilled materials.

Rarely, a landfill may be a monofill, that is it may contain uniform layers of drummed wastes or uniformly placed bulk wastes. More often, the landfill will consist of different types of wastes placed nonuniformly across the landfill in layers separated by intermediate covers of soil. The potential for differential settlement must be considered to be greater in landfills with nonuniform wastes and waste placement procedures.

Bulk wastes behave differently from containerized (e.g., drummed) wastes in settlement characteristics. Bulk wastes behave relatively predictably, much like soils, becoming increasingly consolidated with time, but at a decreasing rate. Containerized wastes may remain relatively undeformed until the containers degrade and collapse, at which time voids will be created, and consolidation will begin.

Settlement by consolidation and secondary compression of bulk waste landfills in which drainage layers are provided will probably be essentially complete before final closure. Compaction of waste materials and installation of drainage layers are recommended to lessen the potential for postclosure settlement and cover subsidence.

The approximate time required for primary consolidation to occur can be estimated for a waste or soil layer if the liquid limit is known for the material and if the shortest distance to a drainage path (e.g., a drain layer) is known. Time, for any degree of consolidation, can be computed more precisely if the compressibility or coefficient of consolidation has been determined for the material.

Of the controlling factors, the distance to a drainage path has the most pronounced effect on consolidation time for a waste layer. This fact indicates the desirability of including frequent drainage layers and of removing liquid from the landfill mass so that most of the consolidation will occur before closure.

The time required for ultimate settlement of containerized (drummed) waste to occur cannot be computed without knowledge of the drum deterioration time. The time cannot be determined, although it is expected to be several years, perhaps several decades, if water infiltration is prevented by an impervious cap and liner system.

The void space around drums or other containers in a landfill can be a major contributor to total postclosure settlement and should be filled with solidifying agents or a free-flowing backfill to minimize the void component of total settlement.

The surest way of avoiding problems associated with postclosure deterioration of drums and the delayed settlement and cover subsidence associated with it may be to ban drums from landfills. Instead, drums can be emptied and crushed or reclaimed. Drum contents can be treated and disposed as bulk waste.

Equations for calculating settlement time should be used more to identify operational landfilling and waste treatment procedures that will minimize settlement time than to predict precise values from theory.

Differential settlement across relatively short distances that may occur within subcells comprising a larger landfill cell is more threatening than relatively uniform settlement across longer distances that may occur across large monofills. For the former, tensional stresses may be sufficient to cause cracks in the cover resulting in leakage of water into the landfill. Those tensional stresses may not develop over longer distances, but ponding of water may occur on the cover barrier, weakening its ability to repel water.

Similarly, tensional stresses are anticipated to cause few or no problems with flexible membrane barriers over large subsidence areas. Locally severe differential subsidence can cause strain sufficient to rupture a flexible membrane or otherwise cause its premature failure.

Two or more central column models for analyzing landfill deformation (settlement) can be used to predict differential settlement between columns and thereby to determine the effect of differential subsidence on the final cover.

Expressions for analyzing the deflection of a beam can be used to identify parameters controlling the deformation of a landfill cover subjected to differential settlement. Once identified, the parameters can be adjusted by cover design and construction procedures to minimize distress to cover components.

Differential settlement can be minimized by compacting wastes during placement, eliminating void space within the landfill, stabilizing liquids before placement, and other considerations. The length of the cover (represented as a beam) subjected to subsidence can be reduced by placing wastes as uniformly as possible to provide uniform support to the cover. The cover soil components can be made more resistant to distress by compacting the cover barrier soils wet of optimum water content.

Final cover components will stretch under differential settlement and must be constructed to withstand tensile strain. The average tensile strain in the cover can be computed, and the maximum value of the differential settlement that can be tolerated by the cover soils can be estimated from that computation.

Plastic soils (soils with high plasticity indexes) should be selected for use as cover components to produce a cover resistant to tensile strain.

Laboratory investigations by others indicate the flexible membrane liners (FML's) (components of the barrier layer in covers) may fail at lower strains than would be expected from manufacturer's data. Every effort should be made to reduce differential settlement potential of the landfill and to design the cover to resist tensile strain.

Landfilled wastes should be compacted or treated where possible to reduce potential settlement. Compaction methods include standard compaction techniques, vibratory rollers, and precompression (preloading and surcharging). Waste treatment methods include addition of fixative agents to render the wastes permanently less compressible.

The stabilization of liquid wastes with pozzolanic materials has been shown to increase compressive strength and lessen settlement potential. Such stabilization could be especially beneficial for containerized wastes.

SECTION 3

LANDFILL CHARACTERISTICS

Landfill settlement and subsidence can always be related to the physical design characteristics of the landfill, the character of the emplaced wastes, and how the filling process was conducted. Careful attention to these factors can minimize subsidence damage. Typical aspects of current characteristics and practices are outlined below.

CURRENT LANDFILL DESIGNS

Hazardous waste landfills that meet RCRA requirements have the following characteristics:

- Pits (cells) are excavated in native soil or rock of low permeability (aboveground facilities enclosed by soil embankments are less common).
- Single- or multicell construction is practiced, the cells isolated by berms and the multicell groups isolated by berms, liners, and covers.
- Depths are commonly 15 to 50 feet but are as great as 100 feet.
- The base of the cell is usually above the water table or aquifer.
- Cells are lined with single or multiple natural or synthetic barriers with low permeability to water (10^{-7} to 10^{-8} cm/sec).
- Cells are equipped with leachate collection and monitoring systems.
- A final cover (cap) of more than one layer is installed; the cover includes a synthetic and/or natural barrier layer.
- Wastes are placed with some care in layers generally 3 feet thick or less and covered with less than 2 feet of crushed rock or soil fill (intermediate cover). Waste and intermediate covers are alternated as the cell is filled.
- Compaction of liners and caps is usually controlled and monitored; compaction of waste and fill is limited and is that obtained by passage of tracked and wheeled waste placement vehicles.
- Final cover caps on closed cells are grassed and may be equipped with settlement plates for subsidence monitoring.

- Operators are required to solidify all liquids enclosed within the cell (no free liquids are permitted).

Several types of landfills are commonly found in the United States. Characteristics of landfills for which descriptive information has been obtained are tabulated in Appendix A. One of the most common is excavated with the waste fill almost entirely below the original ground surface and only the cover above ground. Another type is built essentially above ground with the waste enclosed within embankments or dikes. These two types may be combined to maximize the waste volume in a limited area. In hilly terrain and more commonly in the western United States, cut-and-fill landfills may be constructed by partial excavation of natural valleys and gullies with the construction of an embankment or retaining wall at the lower end. In the past, it was common to take advantage of abandoned quarries or gravel pits, where a large excavation had been created for other reasons. Unfortunately, many quarry or pit types became uncontrolled dump sites.

Hazardous waste landfills vary greatly in areal size. Those observed by the authors range from 1 to 37 acres for a single landfill under one cover. A single facility may contain several landfills under separate covers, collectively enclosing hundreds of acres. Landfill depths are commonly less than 50 feet (fill and liner thickness) but are as great as 100 feet. Associated landfill volumes of the largest fills are as much as 1,250 acre-feet or more than 2 million cubic yards of waste and soil fill. Landfill size is an important parameter in developing models for analysis of settlement and subsidence.

All RCRA-permitted landfills have been required to be lined with natural or synthetic materials capable of preventing contact of waste and leachate with the ground water. The "minimum technology requirements" of the Hazardous and Solid Waste Amendments of 1984 require that new landfills be double-lined with a leachate collection layer between the liners. Draft guidance from EPA's Office of Solid Waste has suggested a membrane liner as the top part and a membrane on a clay layer as the bottom part of the double liner.

Further minimum technology requirements dictate that the landfill cover (cap) be no more permeable than the bottom liner. EPA has interpreted this to mean that the cover must include at least both a membrane and a clay component as the barrier layer.

Existing liners and covers vary substantially from the new requirements and from site to site. Liners may vary from none (relying on the impermeability of the cut soil) to elaborate and thick clay layer and membrane combinations. Covers on recent landfills also vary but are commonly a combination of layers including both a membrane and clay. A classification of geomembranes is presented in Appendix B. Figure 1 illustrates the variety of existing cover configurations, and Figure 2 illustrates a cover that will meet the current RCRA regulations.

As-built final cover surface slopes vary from 1 to 30 percent but are commonly 2, 5, or 8 percent. Draft guidance from EPA's Office of Solid Wastes recommends from 3 to 5 percent.

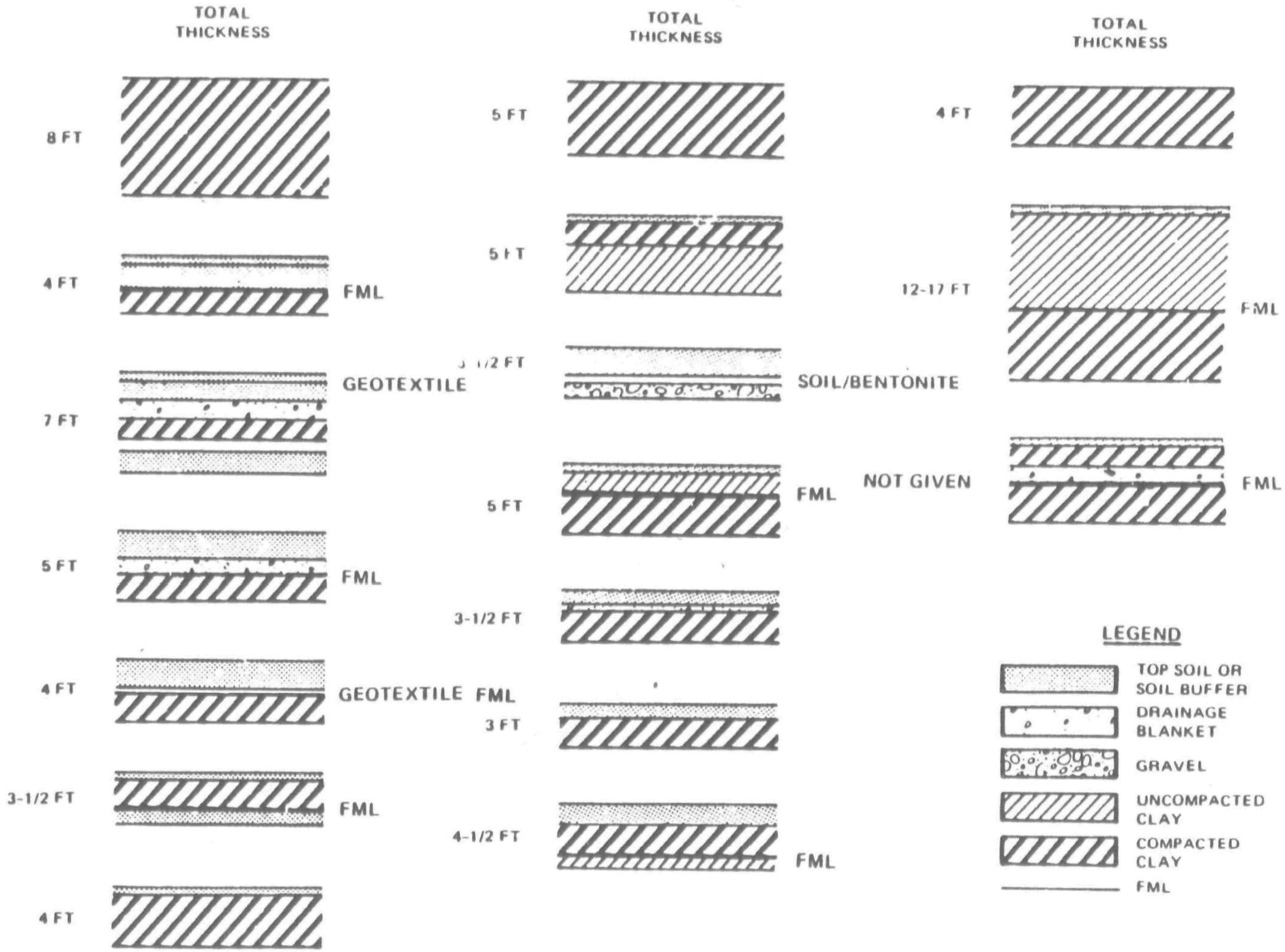


Figure 1. Final covers of actual RCRA landfills.

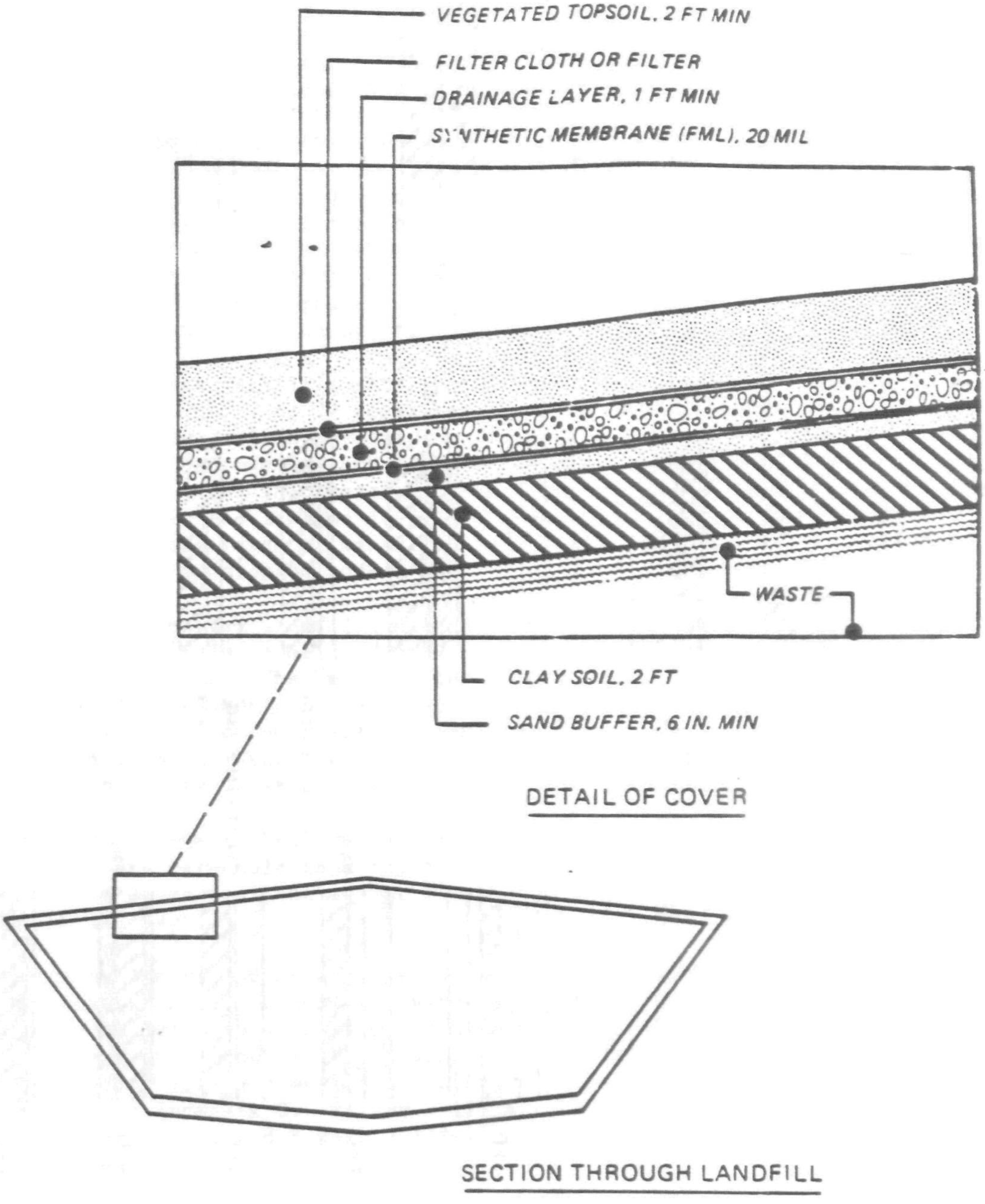


Figure 2. EPA-recommended RCRA landfill cover.

Settlement and cover subsidence analysis must consider the effects of settlement on the clay and membrane barriers of the cover. The clay portion is potentially subject to tensile cracking, thinning, and ponding. The membrane portion is subject to stretching and ponding. The final cover surface slope is subject to being decreased by cover subsidence. Any of these changes increases the possibility of cover leakage and infiltration of water to the waste below.

All landfills meeting RCRA requirements incorporate a leachate collection system into the base of the landfill. Systems vary considerably but commonly consist of plastic perforated pipe imbedded in a granular drainage blanket or in drainage trenches which slope toward a sump for monitoring and removal of leachate via a riser through the fill and cover. The riser most often used appears to be 4-foot sections of concrete sewer pipe added to each lift. Geotextiles are emplaced over the collection pipe of some systems to filter out fines and prevent clogging of the collection lines. In a few landfills accommodations are made to drain the upper portion of the fill by installation of additional drainage arrays within the fill as the landfilling progresses. Commonly, however, the leachate collection array is emplaced only along the base of the landfill.

Good drainage of leachate is desirable for several reasons, including lessening the potential for long-range settlement by allowing more rapid pre-closure consolidation and by decreasing pore water pressure.

CHARACTERISTICS OF LANDFILLED WASTES

Commonly, hazardous waste landfills accept a variety of wastes from several types of industries. Some of the more frequently occurring and abundant wastes include paint waste; electroplating waste; wastewater treatment sludges; baghouse (collector) dust; fly ash; intact, damaged, and crushed steel drums; waste oil and oil-contaminated soil; electric arc furnace dust; filter cake from various dewatering operations; and steel mill pickling liquor.

Hazardous waste landfills may also contain, generally in lesser quantities, more noxious organic chemical wastes such as polychlorinated biphenyls (PCB's) and pesticide waste.

Waste Texture

The liquid content of wastes is extremely important in evaluating settlement potential, for it is often deliquefication or the squeezing out of liquid that accounts for a great part of consolidation.

Hazardous wastes since about 1980 have been treated with solidification (absorption) agents or other materials before being landfilled. Older landfills may contain wastes with much higher liquid volumes, some or most of which may have been in drums. When released, the drainage of the liquids may initiate significant subsidence. Even recent landfills contain liquids from precipitation and run-on that occur during filling.

The recent general ban on free liquids in landfills has been interpreted and enforced in different ways by the regulating agencies. Some states use the EPA-recommended paint filter test to determine whether a waste is a liquid. Several other less sophisticated methods are in use, such as rapping a drum and interpreting the sound, or measuring the "free liquid" over the solids in a drum. From a leachate standpoint, the determination by these methods of whether a waste is a liquid may have merit, but from the standpoint of landfill settlement analysis, it may be more beneficial to evaluate consistency on the basis of compressibility.

Landfilled bulk wastes usually resemble soils in that they can in most cases support the heavy vehicles used to place them within the landfill. Some treated wastes have pozzolanic qualities and "set up" to relatively strong materials of low compressibility. Some solid landfilled materials such as wood and metal products, including steel drum containers, have initially high strengths and compressibilities but are presumed to degenerate and corrode to conditions of low strength and high compressibility with time within the landfill. Prediction of settlement in landfills must consider the delayed compressibility potential of the landfilled materials as well as the short-term potential. The delayed potential may, in fact, be much more significant, as will be seen later.

Waste Densities

Density is an important property of wastes in evaluating the settlement and subsidence potential. In general, greater density means less void space and thus less settlement potential. Densifying the waste is one way of reducing that potential.

Table 1 lists densities for some landfilled bulk wastes and wastes in drums, presumed to be as delivered and measured at the landfill before placement and compaction.

Engineering Properties of Selected Wastes

Reported properties important to settlement analyses include natural (as-delivered) or optimum (laboratory-determined) water content, unit weight, unconfined compressive strength, elastic modulus, shear strength (triaxial compression) data, and compressibility and consolidation data. Table 2 presents selected data for several wastes and simulated wastes. A full report presenting the results of these tests and others is in preparation by the authors. Materials 1 through 12 of Table 2 were laboratory-tested before and after being enclosed in large lysimeters for a number of years and are designated "prelysimeter" and "postlysimeter," accordingly. The three industrial wastes used in the lysimeter tests were an electroplating waste sludge, a chlorine production brine sludge, and a glass etching sludge. Both raw (untreated) and stabilized (treated by mixing with portland cement and fly ash) samples of the wastes were tested.

Materials 13 through 17 are mixtures simulating wastes and consist of mixtures of fly ash and water, fly ash and oil, "kitty litter" and oil, and "kitty litter" and water. Material 18 is an electroplating waste sludge treated with a pozzolanic (portland cement-like) fixation agent. Data for

TABLE 1. REPORTED WASTE DENSITIES FOR LANDFILLED HAZARDOUS WASTES

Bulk Waste	Density
Wastewater treatment plant sludge press cake (bulk, 76% nonvolatile ash, 24% volatiles)	85 lb/cu ft
Wastewater treatment sludge (hard, dry cake)	37
Lime sludge (55% total solids)	86 (wet unit weight) 44 (dry unit weight)
Metal hydroxide sludge	69
Electric arc furnace dust (dry)	62
Electric arc furnace dust (dry powder) (pellets)	70 100
Enamel powder (dry)	74
Fly ash	63
Cement manufacture kiln dust	80*
Cement manufacture baghouse dust	40*
<u>Wastes in Drums</u>	
Lab pack (inorganic oxidizers in jars, cans)	250 lb/drum
Lab pack (oxides, salts in containers)	300 lb/drum
Lab pack (salts, alkalines, solids, and pastes in jars, cans)	500 lb/drum
Lab pack (organic solids, solids, and pastes in jars, cans)	500 lb/drum
Lab pack (organic acids, solids, and pastes in jars, cans)	350 lb/drum
Sludge	450 lb/drum
Lab Pack (organics in glass bottles)	400 lb/drum
Sludge	300 lb/drum
Lab pack (mixed wastes)	300 lb/drum
Hydroxide waste	425 lb/drum
Paint sludge (dry cake)	500 lb/drum
Cured polyester resin still bottoms (moist gel)	600 lb/drum
Waste plating sludge (mud filter case)	545 lb/drum

* Boynton, Robert S., 1980. <u>Chemistry and Technology of Lime and Limestone,</u> John Wiley and Sons, Inc., NY, p 305.

TABLE [illegible]. ENGINEERING CHARACTERISTICS AND PHYSICAL PROPERTIES OF SELECTED WASTES AND SIMULATED WASTES*

No.	Material	Water content (% by weight, as tested)	Dry unit weight, pcf	Unconfined compressive strength, psi	Triaxial Test Results, Peak Deviator Stress (max) in psi, at (confining pressure) σ_3 = [illegible] psi	σ_3 = [illegible] psi	σ_3 = [illegible] psi
1.	Untreated electroplating waste (EPW) sludge, prelysimeter	[illegible]	[illegible]	-		-	
2.	Untreated EPW sludge, postlysimeter	[illegible]	[illegible]	-	1.[illegible]	2.[illegible]	[illegible]
3.	Untreated chlorine production brine (CPB) sludge, prelysimeter	[illegible]	[illegible]	-		-	
4.	Untreated CPB sludge, prelysimeter	[illegible]	[illegible]		Could not be tested, failed under weight of loading cap		
5.	Untreated glass etching sludge (GES), prelysimeter	[illegible]	51.[illegible]	-		-	
6.	Untreated GES, postlysimeter	[illegible]	50.[illegible], 51.6, 52.6	-	[illegible]	5.[illegible]	9.[illegible]
7.	Treated EPW,** prelysimeter	30	[illegible]	[illegible]		-	
8.	Treated EPW, postlysimeter	[illegible]	[illegible]	100.[illegible] (seam of soft, wet material in specimen)		-	
		81.[illegible]	[illegible]	33[illegible] (homogeneous specimen)			
9.	Treated CPB, prelysimeter	[illegible]	[illegible]	[illegible]		-	
10.	Treated CPB, postlysimeter	25	[illegible]	3,31[illegible] (average of two specimens)		-	
11.	Treated GES, prelysimeter	21	[illegible]	26.[illegible]		-	
12.	Treated GES, postlysimeter	52.[illegible]	[illegible]	10.5 (average of two specimens)		-	
13.	Fly ash + oil†	10% oil (=51% saturation)	[illegible]	-	5.[illegible]	9.[illegible]	[illegible]
14.	Fly ash + oil	[illegible]% oil (=[illegible]% saturation)	10[illegible]	-	[illegible]	11.6	10.[illegible]
15.	Fly ash + water	10	[illegible]	[illegible] (allowed to hydrate for [illegible] days, retained [illegible]% water after drying)			
	(2 tests)	10	[illegible]	1,[illegible] (allowed to hydrate for [illegible] days, retained [illegible]% water after drying)			
16.	Kitty litter + water	[illegible], [illegible], 66.6	[illegible]	-	10.6	[illegible]	[illegible]
17.	Kitty litter + 50% oil	50% oil (=51% saturation by oil + 9% by water)	[illegible]	-	13.6	19.0	65.6
18.	Fixed EPW*	-	60	350 after [illegible] days; [illegible] after 29 days			
19.	FGD sludge #1,* sludge:flyash = 1:0.036	(Optimum)	-	[illegible]			
20.	FGD sludge #1, sludge:flyash:water = 1:1:0.56	(Optimum)	-	[illegible] after 0 days; 118 after 42 days			
21.	FGD sludge #1, sludge:flyash:water = 1:2:0.56	(Optimum)	-	16 after 0 days; 106 after [illegible] days			
22.	FGD sludge #2, sludge:flyash:water = 1:1:0.56	(Optimum)	-	[illegible] after [illegible] days; 20 after 14 days; [illegible] after 28 days			
23.	FGD sludge #2, sludge:cement:water = 1:0.15:0.56	(Optimum)	-	[illegible] after [illegible] days; 46 after 14 days; 70 after 28 days			
24.	FGD sludge #2, sludge:flyash:cement:water = 1:1:0.22:0.56	(Optimum)	-	262 after 7 days; 67[illegible] after 14 days; 660 after 28 days			

* Sources of data: 1-17 WES, 18 Reference 1, 19-24 Reference 2.
** Fixation agents: 7-12 portland cement + flyash, 18 portland cement base (proprietary), 19-24 as shown.
† SAE grade 10W hydraulic oil, specific gravity = 0.8[illegible]

material 18 were reported by Webster[1]. Materials 19 through 24 were two limestone scrubber flue gas desulfurization (FGD) sludges treated with different proportions of sludge solids, fly ash and/or portland cement, and water and tested for unconfined compressive strengths (UCS) at optimum water contents. Data for materials 19 through 21 were for one FGD sludge and 22 through 24 for another. Compression tests were performed on remolded (compacted) samples. Table 2 also shows values for UCS after varying setup times after mixing.

The values presented in Table 2 are not a comprehensive collection of waste property data but do represent some common and abundant landfilled waste materials. As such, the values can supply approximate unit weight, strength, and compressibility data for estimating initial and long-term settlement of landfills. Unconfined compressive strength values for treated sludges also show the tendency for wastes mixed with pozzolanic agents to gain strength rapidly with time.

Waste Placement Characteristics

In most hazardous waste landfills, the wastes are placed in rather standard configurations. Unless the landfill is a monofill (containing only one general type of waste), it will be divided into cells for wastes of different chemical character. This segregation is usually to prevent the possibility of detrimental chemical reactions among the materials. The cells will ordinarily be separated by clay berms that are maintained as the landfill progresses upward.

The area and depth of the monofill or the cells are important in their influence on potential cover damage from subsidence. Shorter horizontal dimensions and deeper depths tend to accentuate tensile stresses in the cover. Cellular subdivision of the landfill acts similarly in shortening horizontal dimensions. But this subdivision will also usually segregate the waste into masses of different physical characteristics, separated by berms with still another set of physical characteristics. All of these differences will tend to accentuate differential settlement and cover subsidence.

Wastes are generally placed in the landfill in "lifts" that are simply layers of wastes. It is probably rare that a lift is totally uniform in its physical characteristics across a landfill or a cell. It is probably unrealistic to require uniformity, although that would be ideal for the evaluation and prediction of settlement.

A lift of bulk waste will generally be comprised of many loads of material dumped and spread across the cell. Spreading is most likely to be done by relatively heavy equipment which simultaneously compacts the waste. The lift of bulk material may be a foot or more thick. In some landfills, bulk waste and containerized (most often in steel drums) waste will be found in the same cell, and sometimes in the same lift. Usually drummed wastes will be grouped together, but the horizontal locations of the drum groups may change from one lift to the next. However, in some landfills, containerized waste may comprise an entire cell or even the entire landfill. On the other hand, some operators disallow drummed waste altogether and, if it is received, the drums will be emptied and crushed and landfilled separately.

Intercell and intracell configuration of bulk and containerized waste is one of the most important considerations in evaluating the potential for cover subsidence. In general, bulk waste is the easiest to manage to eliminate a danger of its contributing to postclosure subsidence. This is not to say that it is impossible to control the potential danger from postclosure settlement of containerized waste, but it will be much more difficult.

Waste lifts are often separated by soil layers, especially where lifts are containerized waste. In this case, the primary purpose of the soil layer is to provide a working surface for the next lift. A conscious effort may or may not be given to filling the void space between containers. Bulk wastes may not be separated by soil layers. It does not appear that a great deal of attention is given to the properties of soils that may be used, even though such attention could have a dramatic effect on the amount and rate of ensuing settlement. For example, free-draining soil layers in bulk wastes can accelerate settlement during the preclosure period before the cover is placed. Pozzolanic solidification of drummed waste and the placement of pozzolanic material between drums might eliminate the danger of postclosure settlement and damaging cover subsidence by permanently increasing the compressive strength of those waste layers.

Most hazardous waste landfills are equipped with vertical riser pipes, as noted earlier, extending completely through the waste mass and cover. These riser pipes help to drain run-on and leachate from the waste mass, thus accelerating settlement to some extent during and after the filling process. The riser pipes also help to vent gases that may be generated in the waste, although several vents specifically for gas venting are features of some covers.

Preloading of the waste mass with a temporary soil cover for a period of time before the installation of the final cover has been suggested and occasionally used as a means of promoting settlement prior to final closure.

SECTION 4

ANALYSIS OF POTENTIAL SETTLEMENT AND SUBSIDENCE

SETTLEMENT-CAUSING MECHANISMS

Several mechanisms have been recognized to cause subsidence at sanitary and low-level nuclear waste landfills. These include primary consolidation and secondary compression, raveling or piping of fill soils or debris into voids or cavities, and enlarging and subsequent collapse of voids or cavities in waste fill by corrosion, oxidation, combustion, or biochemical decay. All of these mechanisms are not pertinent to hazardous waste landfills constructed according to current RCRA requirements. Those considered important in hazardous waste landfills, and discussed herein, include primary consolidation, secondary compression, collapse of voids created by waste container deterioration, and decay of waste debris. Primary consolidation and secondary compression are the dominant mechanisms of settlement in soil-like bulk wastes.

The settlement mechanisms cause changes in the waste volume which in turn cause stresses and strains in the overlying cover that may result in surface subsidence.

Framework of the Analysis and Evaluation of Assumptions

Real world situations involving in situ stress, strain, deformation, material properties, and time dependent factors which influence these quantities can never be completely known or modeled precisely. Additionally, there is an element of uncertainty in the geometry of structures such as hazardous waste landfills. Therefore, in the development of a model to predict behavior in such structures, certain simplifying assumptions must be made. The assumption will typically be those made in the development of the theory of consolidation, and it may be important to state these assumptions because the conditions within a hazardous waste landfill may be worse than those within a compacted earthen embankment. Additionally, it should be stated that predictions made on the behavior of well controlled compacted earthen embankments using consolidation theory can be in considerable error simply because real world situations rarely conform to idealized theory.

The assumptions made for this analysis are discussed below.

- The material under analysis is homogeneous. Homogeneity is never fully realized in the very heterogeneous mass of a hazardous waste landfill. The mass is spatially heterogeneous and violates the assumption of homogeneity.

- The material under consideration is saturated with liquid. Saturation in hazardous waste landfills is seldom complete, but complete saturation influences the rate of settlement and subsidence. Settlement occurs more rapidly in an unsaturated fill, so time predictions made with the assumption of complete saturation are conservative.

- One-dimensional compression does occur within a large portion of a landfill which is large in areal extent compared with the depth. However, one dimensional compression does not occur in zones in which there are appreciable shear stresses, such as areas in close proximity to physical boundaries.

- The mass is isotropic. The materials involved are generally soil-like materials which are not isotropic; that is the properties of the materials may vary with direction. Applied compaction may increase the anisotropy of the materials. However, laboratory tests performed on representative materials should be performed on material treated in such a way as to duplicate, as closely as possible, the placement and hence the anisotropy of the material in the landfill.

- Darcy's law is valid, and one-dimensional flow occurs in the landfill. Both of these conditions are in general violated because of inhomogeneity and anisotropy of the materials in question.

- The material is linearly elastic. The materials involved are soils which are not linearly elastic. However, effort is made to develop a treatment which accounts for the nonlinear behavior of the materials in question.

- The action of an infinitesimal mass is no different than that of the larger representative mass. This assumption relates to the fact that a representative small specimen of material may be tested to determine properties which may be used to predict the behavior of the mass. Realistically, the accurate representation of the mass by a small specimen is unlikely because of the heterogeneous nature of a hazardous waste landfill.

The serious violation of many of the stated fundamental assumptions is fully recognized. Similar violations of fundamental assumptions are recognized for beam models (presented later in this section) because beam theory is based on the assumption of small strains, and there is no insurance that strains will remain small in hazardous waste landfills. Evidence will be presented to show that strains may become large. However, it must be realized that in general these models will not be used to quantify the various factors associated with distress in the structures under analysis. Instead the models will be used to identify parameters associated with distress, how these parameters relate to each other, and how they may be manipulated to minimize the effects of distress. The models will be used for qualitative rather than quantitative analysis. In this light, the assumptions necessary for the development of the models become less disturbing.

Primary Consolidation

Consolidation of a soil (or waste) is the decrease in void ratio (the ratio of the volume of voids to the volume of solids) by expulsion of fluids from the voids under excess hydrostatic pore pressure (primary consolidation) and by deformation of the skeleton of the mass and compression of gases in the voids (secondary compression). The decrease in void ratio by consolidation represents a decrease in volume of the mass and can cause the surface of the mass to subside.

The classic Terzaghi theory for one-dimensional consolidation of a soil assumes that the soil is saturated and that deformation of the soil mass is by change in volume caused by expulsion of water from the consolidation.

If a mass of soil of thickness H, diagrammed in Figure 3, is compressed, the change in its thickness, ΔH, can be expressed as a change in the void ratio, Δe. An estimate of settlement expected to occur in a soil by consolidation can be obtained by combining field data with laboratory data on soil compressibility in the equation

$$\Delta H = \frac{C_c H}{1 + e_o} \log_{10}\left(\frac{p_o + \Delta p}{p_o}\right) \quad (1)$$

where

ΔH = amount of settlement
C_c = laboratory-determined coefficient of compressibility
e_o = initial void ratio
p_o = initial overburden or self-weight stress in the field
Δp = increase in stress by the added load

Equation 1 might be used to compute the subsidence in a hazardous waste landfill. However, Equation 1 is developed from the theory of consolidation and therefore suffers the limitations resulting from the assumptions made in the development of the theory. These assumptions and the associated limitations are listed and discussed separately in Section 3. A procedure to compute settlement based on the integration of measured stress-strain properties circumvents some of the assumption of the consolidation theory.

Consolidation of soils by lowering of the water table has been identified as a possible cause of ground subsidence in some locations. The effect of lowering the water table in a soil is to surcharge the soil by increasing the effective stress (the vertical stress minus the pore water pressure) through a decrease in pore pressure. Similar effects can be expected in soil and waste materials in a hazardous waste landfill where the extraction of landfilled fluids through the leachate collection system would result in compression of the mass.

Secondary Compression

Settlement from secondary compression (deformation of the soil mass) occurs later in the loading history of a fill as the applied stress is

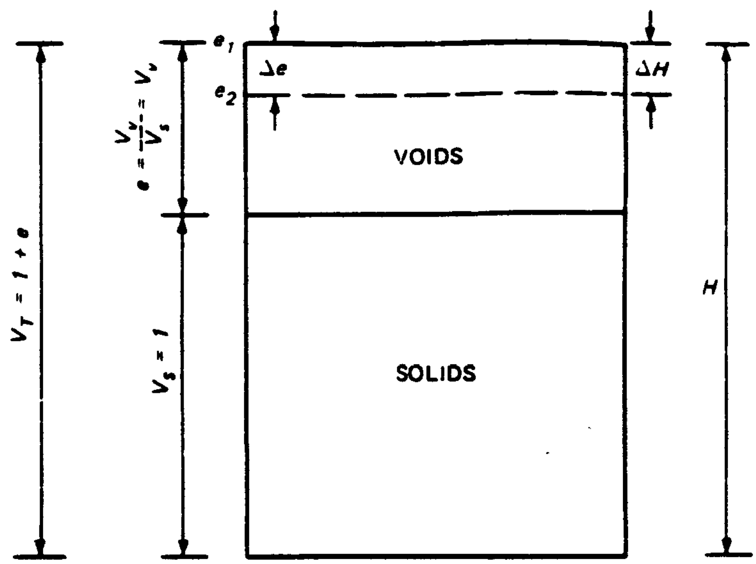


Figure 3. Thickness and volume relationship for a soil mass of thickness H and volume V_1 .

transferred from the pore fluids to the soil skeleton. Secondary compression (H_{sec}) may be calculated from the following equation:

$$\Delta H_{sec} = C_a H_t \left(\log_{10} \frac{t_{sec}}{t_{pri}} \right) \quad (2)$$

where C_a = coefficient of secondary compression from lab
t_{sec} = time for which settlement is significant
t_{pri} = time to completion of 100 percent primary consolidation

The total settlement in bulk waste is the sum of the primary consolida- tion and the secondary compression settlements. It is likely that most bulk wastes initially contain a significant amount of liquid. If that is the case, primary consolidation will be a greater contributor to total settlement than will secondary compression in bulk waste landfills.

Appendix C provides an example of the calculation of total settlement for a landfill.

Container and Fill Deterioration and Cavity Collapse

The dominant settlement mechanism for heterogeneous landfills containing mixtures of debris, bulk, and containerized wastes is not expected to be consolidation. Instead, long-term settlement of heterogeneous hazardous waste landfills should be analyzed on the basis of deformation of the waste layers and deteriorating waste containers.

Most of this type of settlement is likely to take place after, perhaps long after, closure of the landfill. Thus, settlement caused by the collapse of containerized waste may have more potential for subsidence damage to the cover than consolidation settlement, much of which can occur, or can be made to occur, prior to closure. However, it must be emphasized that there is no documentation of subsidence-related problems in controlled (RCRA-regulated) landfills, probably because none are old enough for deterioration to have occurred.

Settlement should result from later filling of larger structural voids within the landfill that remain through the filling process or are created by waste degradation. These voids are expected to survive the primary consolidation and secondary compression because they are supported by initially very stiff materials. Drummed wastes are the most significant case in point.

Initial structural voids consist of unfilled landfill space. Incomplete filling of containers and the space between them is probably the most prevalent example of how such voids are created. Random space in large debris and space created by decay of organic materials are other examples.

The maximum amount of potential settlement should approximate the volume of the larger voids. A small additional amount should result from the consolidation of wastes after they are released from rigid containers.

It should not be construed that the potential settlement resulting from the filling of larger voids will necessarily be significant. Careful placement of containers and debris-type materials with attention to filling voids with lift (intermediate) cover material will keep cavity size small. Sinkhole development by piping should not occur because liner systems preclude the development of escape paths or pipes, and leachate removal systems prevent excessive heads and gradients that might trigger cavity collapse or growth.

PREDICTING LANDFILL SETTLEMENT

A layer or zone of waste or fill soil within a hazardous waste landfill possesses engineering properties that control its deformation (strain) under the load (stresses) imposed on it by materials above and around it in a continuum mechanics model of the landfill. Variable properties including stiffness (Young's modulus), unit weight of materials, and Poisson's ratio (ratio of transverse normal strain to the longitudinal strain in a sample compressed longitudinally) reduce waste layers or zones to units that can be mathematically analyzed (if the landfill satisfies the requirements of the mathematical model). Thus the amount of settlement to expect in initial and degraded waste fill conditions may be estimated. Values of the variables can be changed to reflect changing conditions of stress and material properties in the landfill with corresponding changes in the deformation or settlement. Material properties such as unit weight, modulus, and Poisson's ratio can be determined in the laboratory for actual waste materials and containers or can be estimated from tests on simulated waste materials and standard containers.

Mathematical models constructed to aid analysis of deformation of landfills should recreate the stress conditions and loading history of the fill. For example, because wastes and fill are placed in the landfill gradually over a period of months or years, and the fill depth increases gradually, deeper fill materials are compressed at different rates and under increasing loads as the filling progresses. A model should be used that simulates the process, building up the total structure by stacking one layer at a time on top of the preceding layer and allowing vertical stress and lateral confinement to increase in a systematic manner as the layers are placed. Deformation after closure is controlled by changing strengths and stiffnesses of the waste materials as they degrade and deteriorate, with relatively constant vertical stresses. This later or postclosure settlement can be analyzed based on sudden loading or "gravity release" loading whereby the load to the entire landfill is applied all at once. Such a loading condition would apply after closure (cessation of filling and application of final cap to the fill), after the landfill has undergone initial settlement. Deformation of the postclosure landfill then depends on decreasing elastic moduli of the deteriorating fill contents. Earlier investigations of settlement in hazardous waste landfills used these approaches to predict settlement.

Settlement in Bulk Waste Landfills

In bulk waste disposal, liquid and solid wastes are deposited in the landfill and stabilized if necessary, then compacted into the landfill using some practical, effective, economic compactive effort. Liquid content and compaction effort applied to the waste will determine the amount of settlement which will occur, and there may be a certain economic pressure on the landfill operator to maximize liquid waste content and minimize compaction effort. Such an approach may lead to postclosure settlement problems if taken to extreme. Central column analysis may be used to estimate postclosure settlement based on assumed in situ stress and strain conditions and the ability to select waste samples from which stress-strain properties representative of the mass may be measured. In using the central column model for estimating settlement, stress-strain data from one-dimensional compression tests are required. In using this approach for the analysis of drum disposal, it was convenient and conservative to assume stress-strain linearity. Such linearity may also be assumed for bulk waste disposal analysis, but a more precise method based on actual stress-strain data will be presented.

Assume that stress-strain data from a one-dimensional compression test can be presented in the functional form

$$\varepsilon = f(\sigma) \tag{3}$$

where

ε = vertical strain

σ = vertical stress

The typical shape of such stress-strain data is seen in Figure 4. The "soil" in question is again "kitty litter," a material often used to stabilized hazardous waste.

Assume further that the stress-strain curve may be least-squares fitted to be represented by a polynomial of degree four. (Note: Many computer codes exist which will curve fit polynomials.) From the least squares polynomial fit, the stress-strain data may be written as

$$\varepsilon = a_0 + a_1\sigma + a_2\sigma^2 + a_3\sigma^3 + a_4\sigma^4 \tag{4}$$

where a_0, a_1, a_2, a_3, a_4 are the coefficients of the curve fit. The instantaneous change in stiffness may be obtained by differentiating Equation 4 and is

$$\frac{d\varepsilon}{d\sigma} = a_1 + 2a_2\sigma + 3a_3\sigma^2 + 4a_4\sigma^3 \tag{5}$$

Substituting $\sigma = \gamma y$ into Equation 5

where

γ = material density, assumed initially constant

y = vertical distance below the surface

results in

$$\frac{d\varepsilon}{d\sigma} = a_1 + 2a_2(\gamma y) + 3a_3(\gamma y)^2 + 4a_4(\gamma y)^3 \tag{6}$$

Substituting Equation 6 into

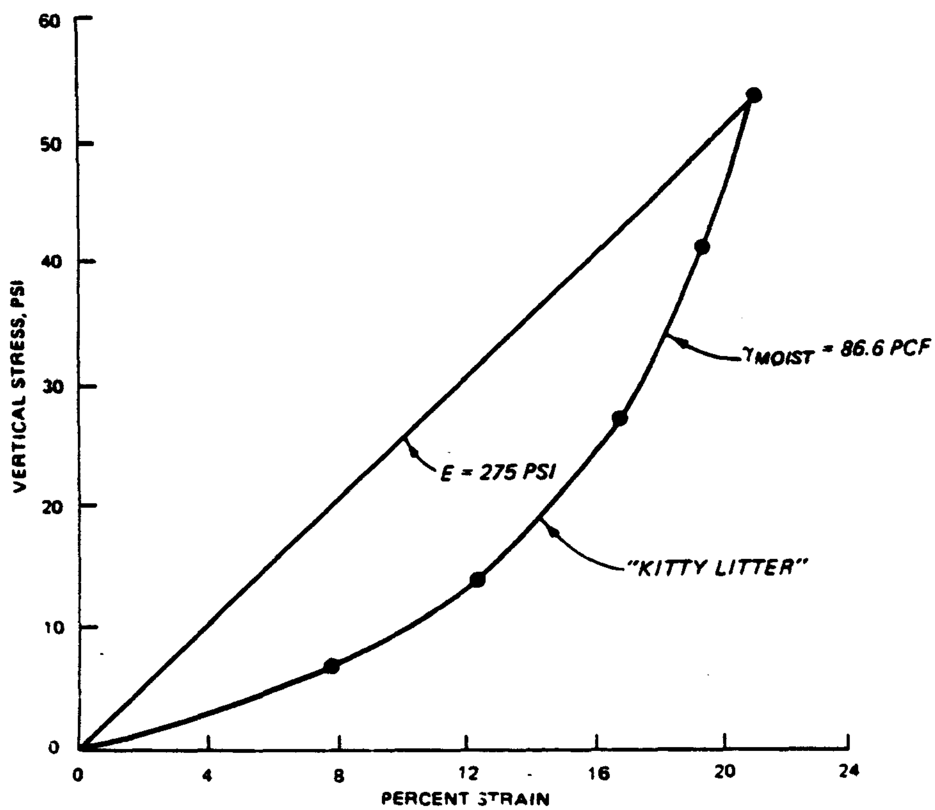


Figure 4. Constrained elastic modulus of waste simulated by "kitty litter."

$$\Delta L = \int_0^L \gamma y \frac{d\varepsilon}{d\sigma} dy \qquad (7)$$

and integrating, the result

$$\Delta L = \frac{a_1 \gamma L^2}{2} + \frac{2a_2 \gamma^2 L^3}{3} + \frac{3a_3 \gamma^3 L^4}{4} + \frac{4a_4 \gamma^4 L^5}{5} \qquad (8)$$

is obtained where

ΔL = subsidence in a central column with nonlinear stress-strain properties

L = depth of landfill

To compare the results obtained from the linear modulus (Equation 3) versus the nonlinear modulus (Equation 8) Table 3 was prepared showing predicted subsidence in a bulk landfill having the stress-strain characteristics of kitty litter.

Stress-strain data for kitty litter are shown in Figure 5. Table 3 shows how the two models predict different values of settlement for different landfill depths and material densities. The table shows that settlement predicted by the nonlinear model is always less than that predicted by the linear model. The nonlinear model predicts less settlement because the stress-strain stiffness modulus of soil increases as soil is deformed in confined compression. Because of the shape of this curve, the secant stiffness modulus value is always less than the average tangent stiffness modulus of the nonlinear curve, and therefore the subsidence predicted by the nonlinear model will be less than that predicted by the linear model. However for shallow depths of landfills (represented by the initially flat part of the curve) the linear and nonlinear models will predict essentially the same value of subsidence. As the landfill becomes deeper and the stress-strain modulus increases, subsidence predicted by the more precise model will diverge, as shown in Table 3. Figure 5 also shows actual data and the data which would be predicted by the polynomial and demonstrate that there can be good agreement between actual and fitted stress-strain data.

Assumptions made in developing this model are that the density at all points along the column element was initially homogeneous, the stress-strain properties used are representative of the entire column, and the column was suddenly "released to gravity" from a weightless state. The last assumption will never be physically approached except in the case of a column in a saturated landfill with very low permeability which was filled rapidly. As was mentioned above, subsidence begins to occur as soon as the first layer of material is deposited in a landfill. This nonlinear central column model will predict the total amount of subsidence which will occur in columns of the waste, in short, an upper bound of subsidence. If this upper bound of subsidence can be tolerated, then the amount of subsidence which is likely to occur

TABLE 3. SETTLEMENT DUE TO LINEAR AND NON-LINEAR STRESS STRAIN PROPERTIES IN KITTY LITTER

a_1 = 0.0168557
a_2 = -0.0005803
a_3 = 1.00011 E-5
a_4 = -6.47878 E-8

γ pcf	L ft	σ_{max} psi	$\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$ psi	Linear ΔL ft	Nonlinear ΔL ft
84	30	17.5	109	2.40	1.93
86	30	17.9	109	2.46	1.94
88	30	18.3	109	2.52	1.95
90	30	18.8	109	2.58	1.95
92	30	19.2	109	2.63	1.96
84	50	29.2	150	4.86	3.27
86	50	29.9	150	4.97	3.26
88	50	30.6	150	5.09	3.26
90	50	31.3	150	5.21	3.25
92	50	31.9	150	5.32	3.25
84	70	40.8	191	7.48	4.60
86	70	41.8	191	7.66	4.61
88	70	42.8	191	7.83	4.63
90	70	43.8	191	8.02	4.65
92	70	44.7	191	8.19	4.67

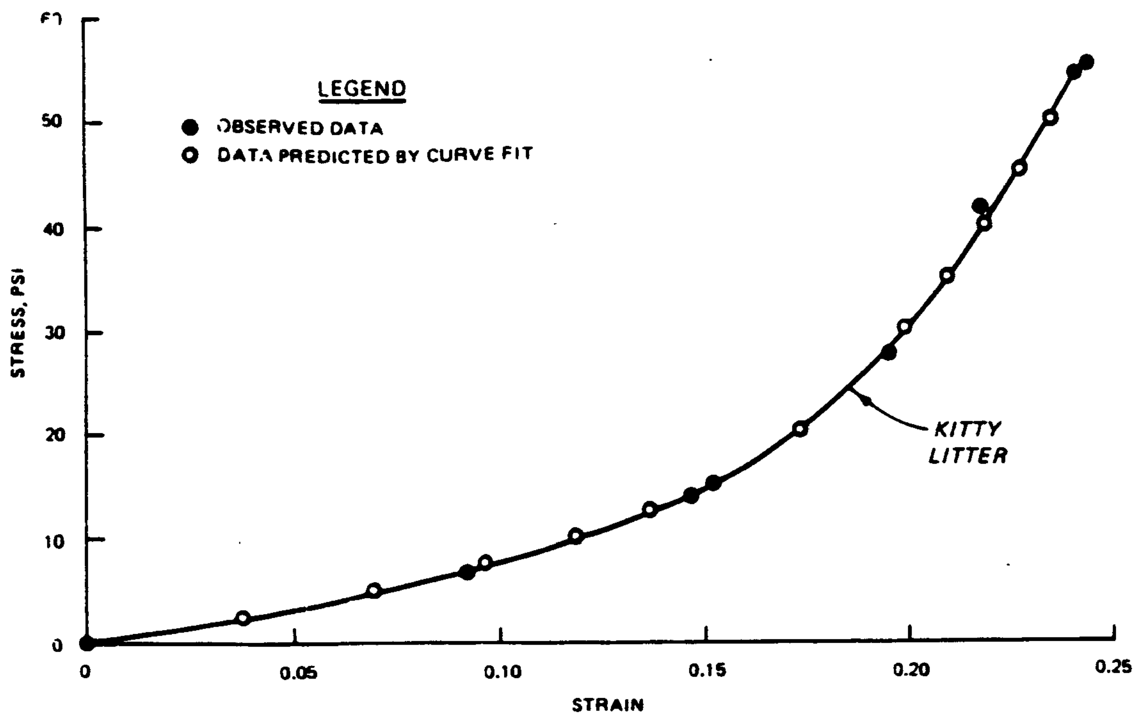


Figure 5. Stress-strain characteristics of kitty litter.

will be less severe since some of the subsidence invariably occurs during filling/construction.

It must be mentioned that the curve fit of stress-strain properties must be carried out with caution since higher order polynomial curves will oscillate between data points. A high coefficient of correlation may be indicated, and the polynomial may predict points on the curve with a high degree of accuracy. However between points the polynomial may oscillate in an undesirable manner as is shown in Figure 6. If such a polynomial were used to predict subsidence, incorrect and meaningless results would be obtained. Oscillation occurs on this stress-strain plot because a few widely spaced points are being fitted with a high degree polynomial. This problem will be avoided if enough closely spaced points on the stress-strain curve are used such that there is no room between points for oscillation. Finally, it may be a good idea to plot the polynomial fit against the actual data to ensure that no undesirable oscillation is occurring and the desired stress-strain data are accurately fit.

Time is not addressed in this nonlinear model. The amount of settlement predicted is the maximum amount which may occur in an unspecified time interval. If the steps outlined below are taken to minimize the time for consolidation and the wastes are properly treated and compacted so as to minimize settlement, then the element of time may be eliminated as a point of consideration. Operating such that time for primary consolidation is minimized may be the only effective means of dealing with time since time effects are poorly understood and therefore very difficult to model.

Settlement in Containerized Waste Landfills

It is the settlement occurring after closure that causes surface subsidence and possible cover (cap) damage. Although, as indicated previously, the landfill can and should be constructed so that most of the settlement will occur before closure, it is inevitable that some will occur later.

Postclosure settlement is likely to be dominated by compression resulting from the closure of structural voids. Only a minor amount will result from the continuation of primary consolidation and secondary compression of bulk wastes. A relatively small amount of postclosure settlement may also occur due to the primary consolidation of wastes released from deteriorated, but formerly rigid, containers.

Structural voids, as noted earlier, are likely to result from the close placement of containers, usually drums, and the inability to completely fill both the drums and the space between them. Some, probably lesser, void space may result from degradation of organic materials and from the unfilled space characteristic of coarse debris waste. The amount of settlement to be expected from closing of structural voids will approximate the total of the structural void space.

It was shown previously (Equation 1) that the void space around drums may be as much as 10.73 percent by volume for drums disposed by burial on their sides and 9.31 percent by volume for drums disposed by on-end (upright) burial. Void space inside drums is difficult to quantify, but current

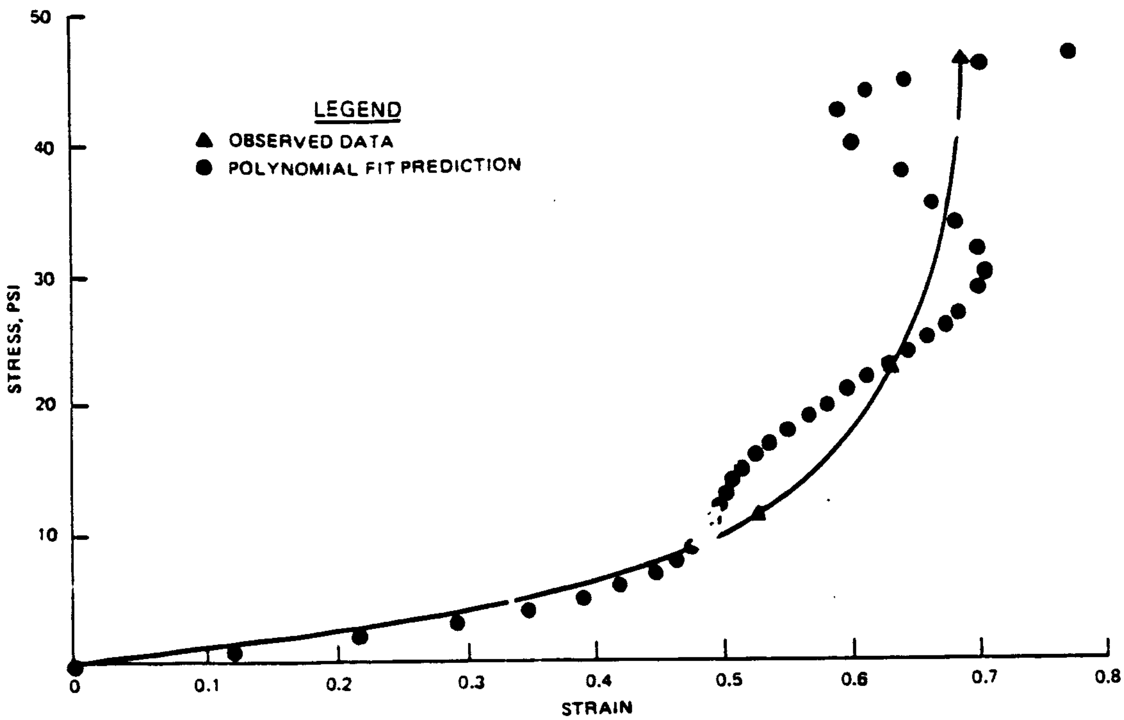


Figure 6. Stress-strain data fit by oscillating polynomial.

regulatory practice limits it to 10 percent. Assuring that this void space is filled completely with a solidifying agent is an obvious way to reduce eventual settlement. Free-flowing backfill such as dry sand or gravel will be the most effective material to fill the void spaces under and between drums to minimize the void component of settlement.

Subsidence caused by the change in stiffness of the waste material inside the drum, after drum collapse, is difficult to quantify accurately. The expression developed from Equation 1 was

$$\Delta L = \frac{\gamma L^2}{2} \frac{1 + \nu}{1 - \nu} \frac{1 - 2\nu}{E} \tag{9}$$

where

ΔL = the subsidence due to the change in stiffness between the barrel and waste

γ = density of the waste material

L = thickness of the combined waste layers

$(1+\nu/1-\nu)(1-2\nu/E)$ = reciprocal of the slope of the constrained modulus from one-dimensional compression of the material in question

The subsidence predicted by Equation 9 will be conservative (more than actually occurs) because it assumes linearity of the constrained modulus. Actually the stress-strain curve is nonlinear, with the rate of strain increase diminishing as stress increases (see Figure 5).

Drums are usually placed in layers, one to three drums thick, with an intermediate cover of soil separating the layers. The intermediate cover layers are generally well-compacted during construction and do not pose a long-term consolidation problem. However, with time, the mild steel of which most waste drums are made will corrode and may weaken to the point of total collapse, subjecting the contents of the drum to compression and volume change which will cause subsidence in the landfill. In this light, the use of drums may create the problem of prolonging the time over which subsidence occurs.

It is not possible to predict the time of drum collapse. Maintaining the integrity of the landfill cap, liner, and leachate collection system will tend to keep the drums dry and extend their lifetime. However, the contained materials may be more or less corrosive in themselves. In addition, there is no reason to expect that containers will all degrade uniformly. It would seem more likely that they would degrade, each on its own schedule, over an extended period. The beginning of deterioration might begin with the first drum perhaps a decade after closure, while the last might occur a century or more later. The surest way of avoiding problems with drums is to ban drums from landfills, or to ban intact drums. Drums of waste can and have been emptied of their content, crushed, and then placed in the landfill. The drum contents are fixed or treated and then applied to the landfill where they are less of a problem. Drums can also be emptied and recycled (reclaimed). Drum recycling center or services are available in some states.

Intentionally increasing the compressive strength of the contained materials and the fill materials between the drums may prevent compression and subsidence from this cause even if the drums fail. Mixing the waste and filling void spaces with pozzolanic materials such as lime and fly ash could provide the needed strength.

Analysis of Settlement Time

An analysis of time is necessary to estimate the portion of total settlement that occurs prior to closure. Any preclosure settlement reduces the amount that can occur after closure and is therefore beneficial in preventing cover subsidence. In addition, preclosure settlement benefits the operator by allowing more space for disposal of additional wastes. As indicated earlier, preclosure settlement is likely to be limited to consolidation of the bulk waste and soil portions of the fill material. Preclosure settlement goes largely unobserved and unmeasured, and thus it is difficult to quantify.

Consolidation time can be estimated. If it is less than the time required for waste placement, consolidation of the bulk wastes and intermediate soil layers can be assumed to have occurred prior to capping and will not contribute to subsidence. An expression to estimate the time required for 90 percent consolidation was derived from the theory of consolidation and is as follows:

$$t_{90} = H_C^2 \times 10^{(0.0168LL-2.2)} \qquad (10)$$

where

t = time in days for 90 percent primary consolidation

H_C = shortest path to drainage in a saturated medium, cm

LL = the liquid limit of the material, percent

Certain simplifying assumptions were necessary in Equation 10, the details of which are given by Murphy and Gilbert.[3] However, the time computed using Equation 10 will be conservative because the theory assumes complete water saturation which will be slower than for the case of partial saturation, and the curve fit incorporating liquid limit into the equation was chosen as an upper (conservative) bound.

If, as an example, a waste or soil layer is 18 inches thick and has access to drainage (e.g., a drainage layer) on either side, than H_C in the equation is 9 inches or 23 centimetres. If the liquid limit of the soil is 60 percent, then the time computed for 90 percent primary consolidation from Equation 3 is 34 days, meaning that 90 percent of the settlement which will occur in that layer will take place in 34 days. Therefore, most of the compression which will occur in layers of a landfill to which drainage is provided will probably occur during construction.

Varying the thickness of the waste or soil layer or the distance between drainage layers illustrates the great effect that layer thickness has on the time of consolidation. Halving the thickness cuts the consolidation time by a factor of 4.

More precise (but still approximate) estimates of primary consolidation time may be made by performing laboratory consolidation tests on the actual materials to determine the coefficient of consolidation. Then the time, t, to achieve an average percent consolidation, U, can be predicted with the equation

$$t = \frac{TH_C^2}{C_v} \tag{11}$$

where

T = a dimensionless time factor which is a direct result of the mathematical solution of the partial differential equations describing the consolidation process.

H_C = length of drainage path for expulsion of water from the soil voids (for single drainage, as with soil overlying an impervious barrier, $H_C = H$; for double drainage, as with soil bounded above and below by pervious zones, $H_C = H/2$; for multiple drainage paths, as with soil interspersed with alternate layers of pervious zones, H_C = fraction of H).

C_v = coefficient of consolidation, a laboratory-determined value dependent on the soil's compressibility, permeability, and density (void ratio).

The exact values of T must be determined by evaluating a rather complex series expression by trial and error. However, this is not necessary since it has been found[4] that T may be evaluated with high precision using the empirical expression

$$T = \frac{\pi}{4}\left(\frac{U}{100}\right)^2 \quad (U < 60\%) \tag{12}$$

$$T = -0.9332 \log_{10}\left(1 - \frac{U}{100}\right) - 0.0851 \quad (U > 60\%) \tag{13}$$

where U = percent consolidation desired.

Consequently, if the coefficient of consolidation, C_v, is determined for a material in a hazardous waste landfill, then the time for any desired percent of consolidation may be computed from Equation 11. In a more general form, Equation 11 may be written (see derivation in Appendix D).

$$t = \frac{TH_c^2\left(\frac{d\gamma_d}{dp}\right)\gamma_w}{k\gamma_d} \tag{14}$$

where

γ_d = dry density of the waste material

$d\gamma_d/dp$ = slope of the dry density versus pressure relationship determined from a one-dimensional compression test on the waste material

γ_w = density of water

k = coefficient of permeability of the waste material

The various factors of Equation 14 may be evaluated to determine how they will affect the time to achieve desired percentages of primary consolidation. Obviously the factors in the numerator of Equation 14 must be minimized and factors in the denominator must be maximized to minimize the time for consolidation.

The time factor, T, and the density of water, γ_w, cannot be changed in the equation, but the other factors may be manipulated to achieve consolidation in the shortest possible time. For example, H_c may be manipulated to advantage by installing drainage layers within the landfill. It should be mentioned again that H_c has the most pronounced direct effect on consolidation time.

The compressibility of the waste material is given in this treatment as $d\gamma_d/dp$, and this quantity will be minimized as the strength and density γ_d of the material are maximized. This can be accomplished by applying compaction effort to the landfill wastes and cover layers; selecting a material of low compressibility (low plasticity index) to serve as intermediate cover where possible; stabilizing the wastes and intermediate cover with pozzolanic agents to increase their compressive strength; and compacting the intermediate cover layers dry of optimum if they are clay-like, also to increase their compressive strength (a caution here is that subsequent wetting can cause collapse* of low plasticity material).

Finally, the time for consolidation may be minimized if the coefficient of permeability, k, of the landfill materials is maximized. Since permeability generally decreases as density increases, efforts to maximize both may be counterproductive. A good compromise may be to compact the soil or waste to optimum density for the effort applied.

In order to calculate time from Equation 11, C_v must be determined. This parameter is usually evaluated using a curve-fitting procedure applied to the time-consolidation curves from one-dimensional compression tests. The procedure (logarithm-of-time method) is given in many standard references.[5,4]

The values of C_v are different for each load increment and therefore must be evaluated for all load increments used in the compression test. To compute the time for various degrees of consolidation for layers of material in the field, an appropriate value of C_v, corresponding to the average

* Collapse is a phenomenon which can occur in low plasticity soils at low density (compacted dry of the optimum water content) when exposed to water. Wetting such a low plasticity soil may soften clay binder between larger silt and sand size particles causing a loss in strength which is accompanied by a large volume decrease. Collapse usually occurs rapidly when compared to the time for comparable volume change due to the process of consolidation.

pressure in the field situation is selected and the time for field consolidation is computed from Equations 11, 12, and 13.

Because of the simplifying assumptions made in the development of the theory and uncertainty in the evaluation of C_v, time predicted by the theory is at best approximate and at worst only an order of magnitude estimate. The problem of selecting an appropriate value of C_v is additionally complicated by the inhomogeneous nature of the contents of a hazardous waste landfill and the difficulty of representatively sampling these materials for testing. The problem is additionally complicated because of the inherent differences in behavior between laboratory samples and in situ soil.

Rather than trying to predict precise values from the theory, it may be much more practical to use the geometric and material properties dictated by the theory to identify general operational procedures that will minimize settlement time. Drainage layers to control the effective thickness of waste layers (H_c) appear to be a practical measure to monitor and control the internal movement of fluid within the facility and to eliminate extended periods of settlement. Previous soil drains and, in more recent time, geotextile fabric drains[4,6,7] have been used to relieve pressure and control flow within earthen embankments. The same techniques may be used to great advantage in hazardous waste landfills.

Differential Settlement

Problems with differential (uneven) settlement may occur if drummed waste must be disposed of in a landfill with bulk waste. The time for deterioration of the steel drum may be quite long and drummed waste layers may remain very stiff in the interim. In such instances, if there are not many drums for disposal in a landfill, they may be dispersed about the landfill, or emptied, the contents stabilized, and the drums crushed or reclaimed. Obviously drums of unstabilized liquid are to be avoided because once the drum is corroded, the entire volume of the drum becomes a large void.

As discussed below, differential settlement is aggravated if stiff and undeforming columns of material are placed in close proximity to flexible deformable columns. Since the central column model is actually based on column elements, if spatial properties within the landfill are known with sufficient confidence, the subsidence of two columns may be computed with the central column model. The difference between the subsidence of the two columns is the quantity described below. Knowing the distance ℓ between the columns, the index of the differential settlement, Δ/ℓ, may be computed and the methods used to analyze the effect of this amount of differential settlement on the cover system.

ANALYSIS OF DIFFERENTIAL COVER SUBSIDENCE

Identification of Causative Factors

Settlement of the waste mass in a hazardous waste landfill will result in subsidence (sinking) of the cover (cap). Differential settlement can lead to cover damage and leakage caused by the tensile stresses created. In such a case, the cover system would be required to bridge the zone of lost support. For this reason, it is reasonable to formulate a model to determine the important factors involved in differential settlement using elementary beam theory. The model assumes that the cover system will lose support over a length, ℓ , and as a result will undergo a differential settlement. The model representation is therefore a beam with fixed supports at either end and is distorted when one support settles an amount Δ (see Figure 7).

Expressions for vertical shear, moment, slope, and deflection of the idealized cover may be determined by integration using elementary beam theory.[8] The mathematical expressions for maximum stress due to shear and moment in the beam model in Figure 7 are

$$\sigma_{shear} = \left(\frac{3}{2}\right)\left(\frac{\Delta}{\ell}\right)(E)\left(\frac{h}{\ell}\right)^2 \qquad (15)$$

and

$$\sigma_{moment} = (3)\left(\frac{\Delta}{\ell}\right)(E)\left(\frac{h}{\ell}\right) \qquad (16)$$

where

σ_{shear}, σ_{moment} = maximum stress due to shear, moment
ℓ = length of beam
E = Young's modulus of the cover material
h = cover thickness

Although these expressions were developed using small-deflection beam theory and may not be appropriate for the large deflections observed in soil structures, the expressions identify parameters which quantify distress caused by differential settlement. For example, Equations 15 and 16 suggest that stress is minimized if Δ/ℓ , E , and h/ℓ are minimized. Obviously Δ/ℓ is minimized if the differential settlement, Δ , is minimized. This may be accomplished by minimizing total settlement and involves compacting wastes during placement, eliminating void space within the landfill, stabilizing liquids before drum disposal and other considerations (Equation 7).

Additionally, Δ/ℓ may be minimized by maximizing ℓ . This will reduce cover stress by spreading the distortion over a greater length and therefore reducing the effect of the distortion. The ℓ may be maximized by placing the landfill wastes as homogeneously as possible to give uniform support to the cover.

Minimizing Young's Modulus, E , of the cover material can be accomplished by compacting the cover soil wet of the optimum water content. This will result in a cover with lower strength but with greater pliability and capacity to distort without rupture. This is shown in Figure 8 which is taken from Lambe and Whitman[4]. The figure shows that samples 1 and 2, which are compacted dry of optimum water content, offer high strength and stiffness (Young's Modulus) but exhibit brittle behavior in that they develop maximum strength and fail at relatively small strain. Samples 5 and 6, compacted wet

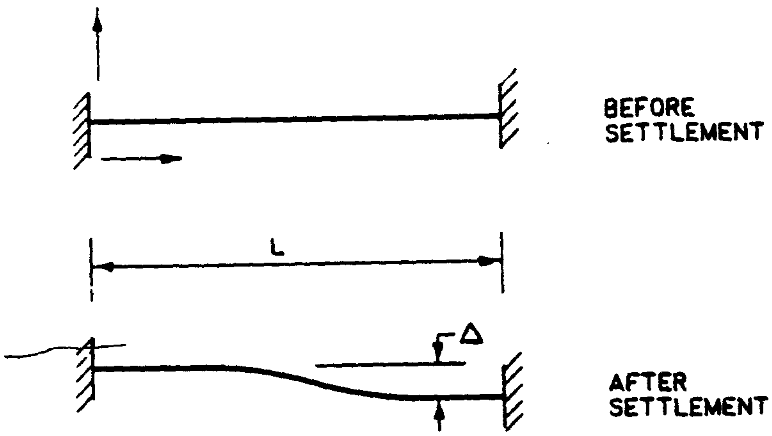


Figure 7. Beam representation of a cover system.

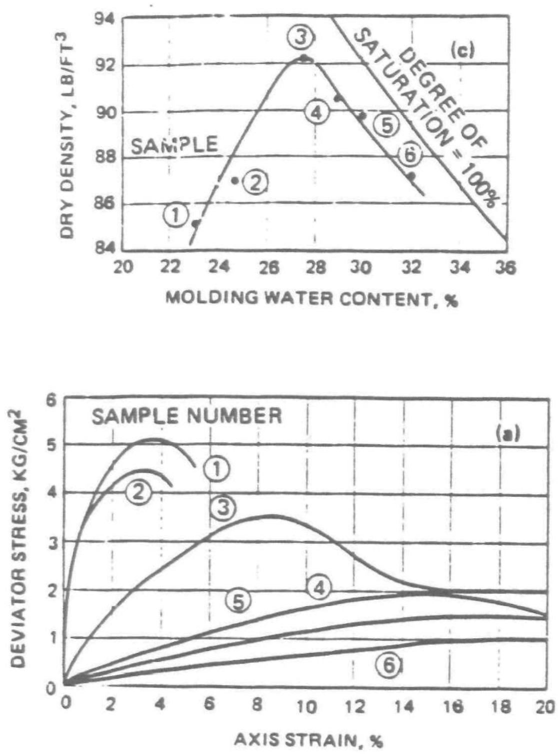


Figure 8. Stress-strain behavior of clay specimens at different compaction condition.

of the optimum water content, show low strength and stiffness but exhibit ductile/pliable behavior.

High strength is seldom required in the cover system of a hazardous waste landfill; therefore, wet-of-optimum compaction of the cover system would be desirable since it would result in a material which would be more able to yield and flow without rupture. It thus would be able to conform to nonuniform settlement in the foundation soil underneath. An additional "free" benefit of the wet-of-optimum compaction is a lower cover permeability.

Finally Equations 15 and 16 suggest that the ratio h/ℓ should be minimized. This should be done by maximizing ℓ. A thick cover is necessary to control diffusion as well as to prevent the intrusion of animals and plant roots into the landfill. A thick cover also offers the advantage of more resistance to desiccation due its large mass and thickness.

The beam model shown in Figure 7 is a very simplified model, but is useful in that it is not used for analysis but rather to identify parameters significantly affecting the behavior of cover systems. That is, the model is used in a qualitative rather than a quantitative sense. However, a more complex model consisting of a beam supported by an elastic foundation is worthwhile considering if only to verify that significant parameters have not been overlooked or omitted by the simpler model. For completeness, three conditions were investigated considering beams supported by a Winkler foundation. A Winkler foundation is a linearly elastic foundation consisting of springs of constant stiffness, all in close proximity (adjacent) to each other but all of which behave independently of the influence of neighboring springs. This representation more closely approaches the behavior of soil supported structures but departs from actual behavior in that soils are not elastic, and elements of soil are influenced by the behavior of neighboring elements.

Three cases are considered and are shown schematically in Figure 9. They are a case where the cover beam bridges a zone where interior support is much less than that at the edges, a case where the cover beam bridges a zone where interior support is completely lost under the central span but the beam is fully supported (clamped) at the edges, and a case where the cover beam bridges a zone where interior support is lost and the edges have less than total support.

For all three cases the beams in question have stiffness, EI, and density, γ. Solutions for cases 1 and 3 are given by Hetenyi[8]. Case 2 is the case of a beam with no rotation or deflection allowed at the ends.

Case 1--

For the configuration of case 1 the maximum moment and shear are located at points A and B as shown in Figure 9. Values of the maximum moment and shear are

$$M_{max} = -\frac{\gamma bh}{2\lambda^2}\left(\frac{\sinh \lambda\ell - \sin \lambda\ell}{\sinh \lambda\ell + \sin \lambda\ell}\right) \tag{17}$$

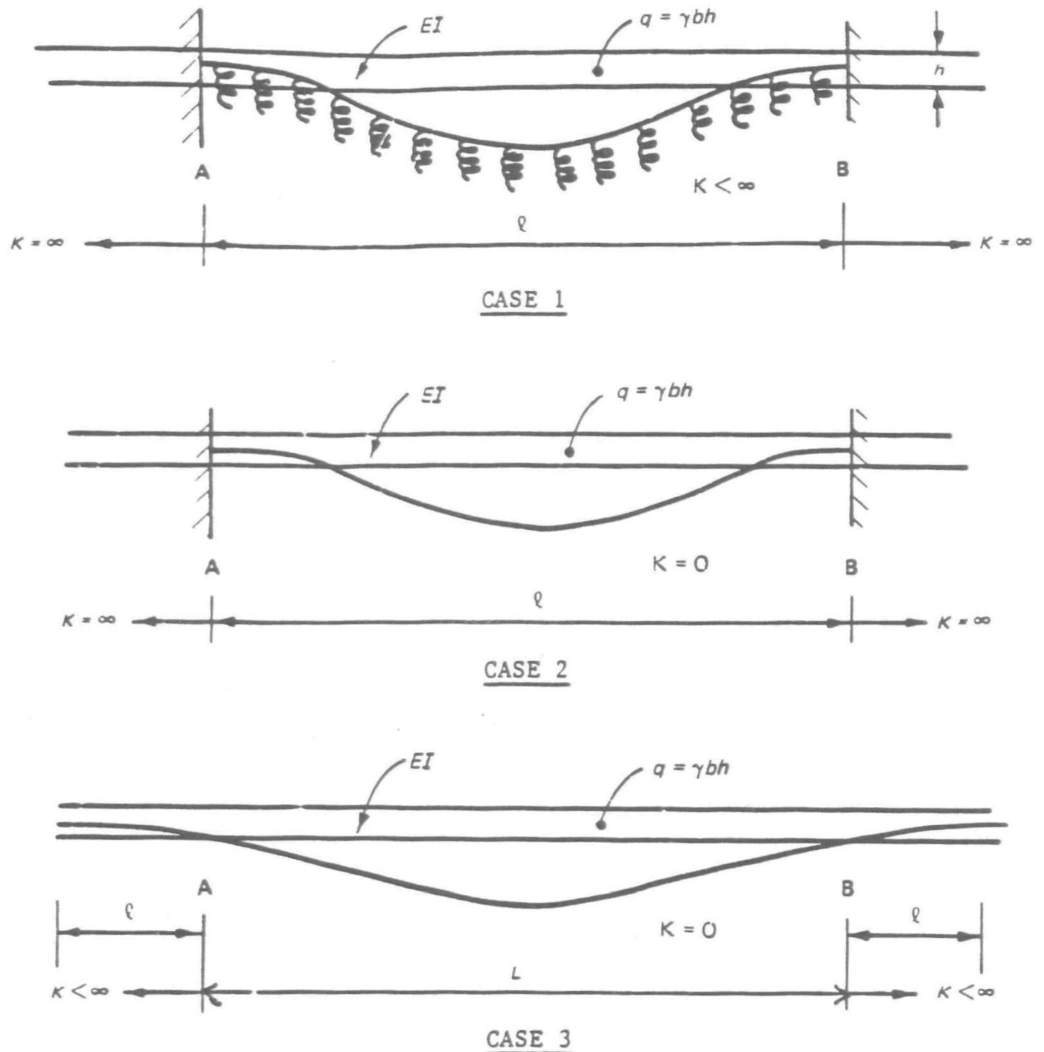


Figure 9. Models of beams on the elastic foundations.

$$Q_{max} = \frac{\gamma bh}{\lambda}\left(\frac{\cosh \lambda\ell - \cos \lambda\ell}{\sinh \lambda\ell + \sin \lambda\ell}\right) \quad (18)$$

where

γ = density of (soil) beam
b = width of the beam
h = thickness of the beam
$\lambda = \sqrt[4]{K/4EI}$
K = foundation modulus (from plate load test)
ℓ = length of beam supported by foundation of modulus K
$I = (1/12)\ bh^3$

From Equations 17 and 18 the maximum stresses due to moment and shear may be computed to be

$$\sigma_m = C_1 \frac{\gamma\sqrt{bh}\sqrt{E}}{\sqrt{K}}\left(\frac{\sinh \lambda\ell - \sin \lambda\ell}{\sinh \lambda\ell + \sin \lambda\ell}\right) \quad (19)$$

and

$$\sigma_s = C_2 \frac{\gamma\ \sqrt[4]{bh}\ \sqrt[4]{E}}{\sqrt[4]{K}}\left(\frac{\cosh \lambda\ell - \cos \lambda\ell}{\sinh \lambda\ell + \sin \lambda\ell}\right) \quad (20)$$

where C_1 and C_2 are constants. From Equations 19 and 20 it is observed that distress will be minimized if γ, bh, E and the trigonometric expression are minimized and K is maximized. This seems consistent with intuition since induced stress will increase if the density (unit weight) of the beam increases over a span with less than complete support. However, the density of the beam and its depth, h, are largely uncontrollable, density being essentially constant and h is usually dictated by factors outside the realm of soil mechanics. E should be minimized as predicted by the simpler model, and F should be maximized since the greater the foundation support, the lesser will be the beam distress. The trigonometric expressions in Equations 19 and 20 are bounded between zero and one. If $\lambda\ell$ is zero then the expression becomes zero. However, $\lambda\ell$ is generally not equal to zero, so ℓ must be zero which reduces the problem to a trivial case. If $\lambda\ell > \pi$, then the trigonometric expression approaches one. The condition $\lambda\ell > \pi$ represents the case of a long beam.

The conclusion reached by this analysis is that case 1 is consistent and compatible with the beam model.

Case 2—

For case 2, the maximum stress due to shear and moment becomes

$$\sigma_m = \frac{\gamma\ell^2}{2h} \quad (21)$$

and

$$\sigma_s = \frac{3}{4}\ \gamma\ell \quad (22)$$

Case 2 may represent the case of a cover fully supported until it loses support over a length, ℓ such as if a single drum or series of drums collapsed within a landfill causing cover support loss, or if settlement occurred in the waste material underneath the cover. Distress due to both moment and shear may be minimized by minimizing the unsupported length ℓ which may be accomplished by providing adequate compaction of wastes so that foundation support is not lost over a larger distance ℓ, or not burying drums which otherwise would ultimately collapse with the consequent loss of cover support.

Case 3--

In case 3 the maximum stresses due to shear and moment are

$$\sigma_m = \left(\frac{\gamma}{2}\right)\left(\frac{L}{h}\right)\left(\frac{5 - \lambda^2 L^2}{2\lambda + \lambda^2 L}\right) \tag{23}$$

and

$$\sigma_s = \frac{3}{4}\gamma L \tag{24}$$

Both Equations 23 and 24 suggest that γ and L should be minimized for minimum cover distress, but these limits lead to trivial examples. From Equation 23, however, it may be determined that distress due to moment is minimized if the product $\lambda L = 6$, which produces the very interesting result that the relationship between unsupported length L, the foundation constant KI, and the beam E and geometric parameters b and h for minimum distress are

$$L = \sqrt[4]{\frac{12Ebh^3}{K}} \tag{25}$$

Equation 25 suggests that a certain degree of foundation flexibility may be desirable because if the foundation modulus becomes infinitely large, case 3 degenerates to case 2, which is that of a cover with fixed ends and represents a condition of more severe distress than that of case 3. A gradual transition in foundation support to minimize distress in the beam (cover) is suggested by Equation 25 along with the comparison of cases 2 and 3 and reinforces the suggestion of the earlier simple model that distress is aggravated in a cover system if there is a sudden change in stiffness of the foundation, i.e., wastes of great differences in stiffness should not be placed in close proximity to each other.

Tensile Strain

The cover system will be required to increase in length and therefore carries tensile strain as differential settlement occurs in a hazardous waste landfill. The cover will crack if tensile strain becomes excessive. Generally soils are not able to withstand high levels of tensile strain without cracking.

The average tensile strain developed within the cover may be computed using the simple beam model. This procedure involves integrating over the deflected beam shape to determine the arc length of the beam after deflection. An expression to compute the arc length of the deformed section of the beam model shown in Figure 7 may be determined by integration, and is

$$\ell = \int_0^{\ell} \left(1 + \left(\frac{6\Delta}{\ell}\right)^2\right)\left[\left(\frac{x}{\ell}\right)^2 - 2\left(\frac{x}{\ell}\right)^3 + \left(\frac{x}{\ell}\right)^4\right]^{1/2} dx \qquad (26)$$

where

ℓ = length of the deformed cover element
Δ = differential settlement
ℓ = length of the cover element
x = coordinate along the cover element

Equation 26 requires numerical integration because closed form integration of the expression is not possible. The results of this integration are shown in Figure 10 and are presented as the dimensionless quantity Δ/ℓ versus average tensile strain in the cover. Figure 10 also shows how the average tensile strain increases as differential settlement given as the normalized parameter Δ/ℓ increases.

If the maximum tensile strain which can be sustained by a given soil is measured, estimated, or otherwise obtained, then the maximum value of Δ/ℓ which can be tolerated in a cover system of that soil may be estimated from Figure 10.

Figure 11 is a plot of maximum tensile strain reported by several investigators[9,10] versus soil plasticity index. Figure 11 also suggests that the capacity for tensile strain increases as plasticity index of a soil increases. For completeness, more research on the tensile strain capacity of soil is needed, but the trend for Figure 11 is clear, showing that, for similar conditions of compaction (water content and dry density), the tensile capacity of a soil increases as the plasticity index increases. Therefore, since soils that are able to withstand higher levels of tensile strain are preferred for the construction of cover systems of hazardous waste landfills, the selection of soils with higher plasticity indices is indicated if a selection is possible.

Additionally, it should be stated that it would be highly desirable to perform a laboratory study of the tensile properties of potential soils of which the cover system of a hazardous waste landfill will be constructed. The investigation should include (for the soil selected for the cover) several molding conditions to determine the condition which offered the best combination of tensile strain, economy, and ease of placement for the differential settlement condition anticipated. For areas in which a limited selection of soils is possible, plasticizing by the addition of soils such as bentonite may be considered.

Effects of Differential Subsidence on the FML

The discussion of subsidence and settlement effects has thus far focused on deformation of the soil portion of the cover. Effects of settlement on the

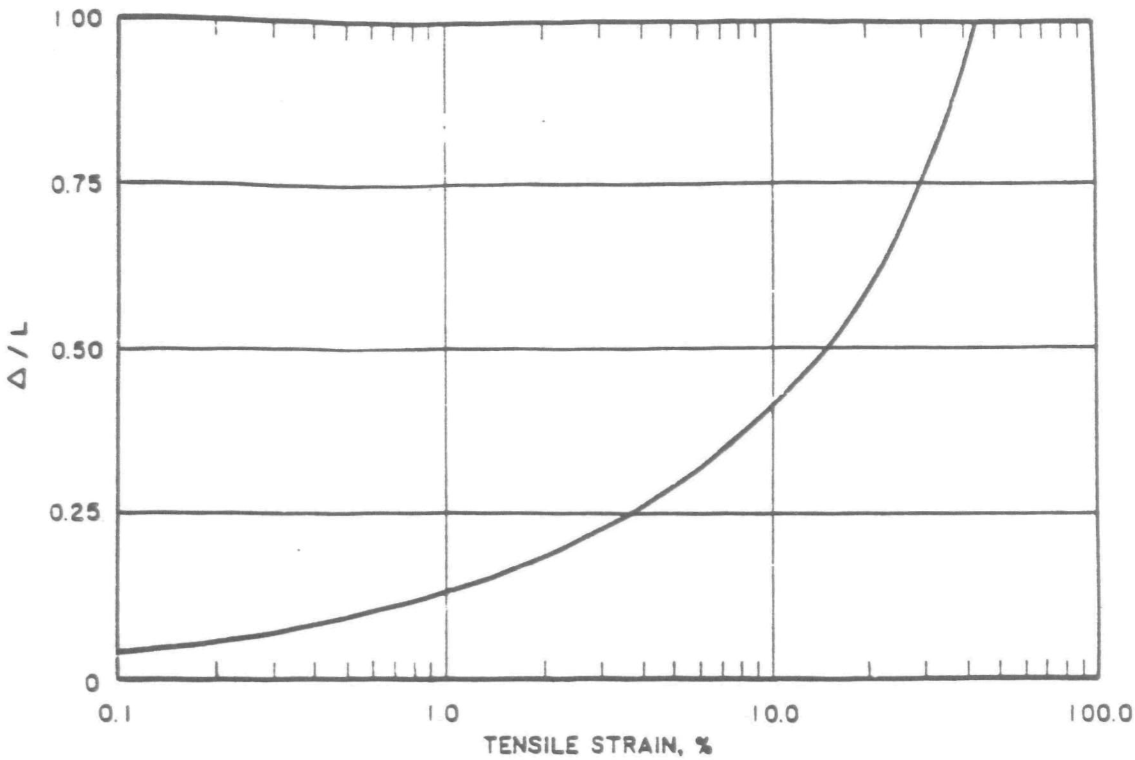


Figure 10. Δ/ℓ versus average tensile strain.

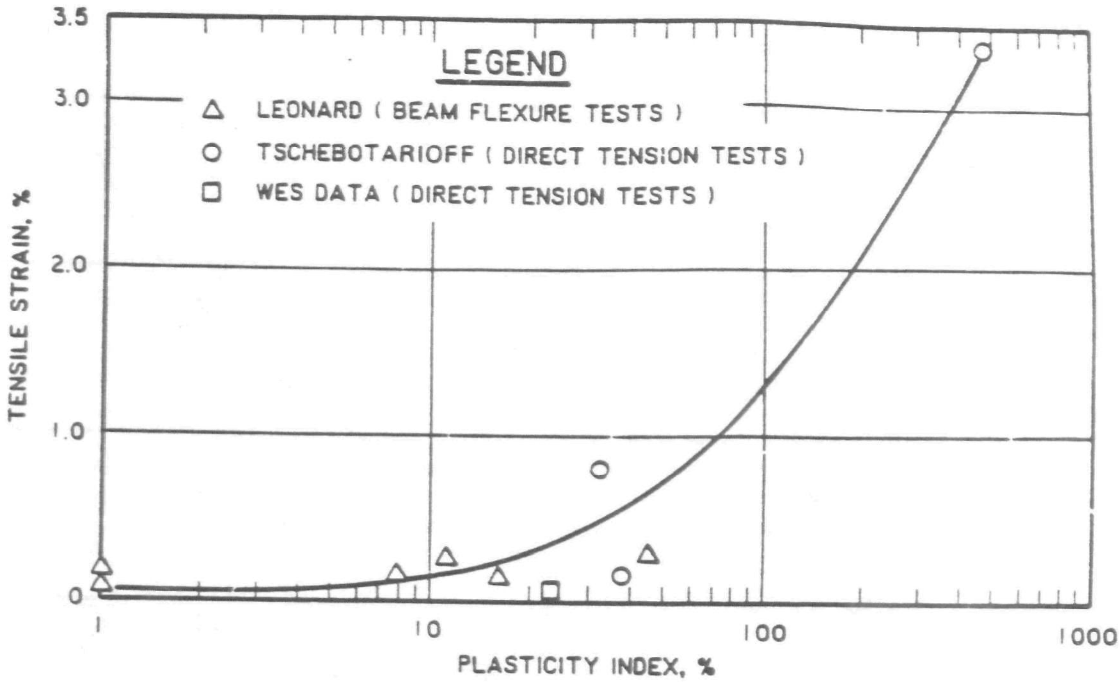


Figure 11. Tensile strain versus plasticity index.

FML of the cover must also be considered. Field data on FML performance in hazardous waste landfills are not available, but laboratory tests have been conducted on FML's under simulated fill and embankment conditions[11,12]. Flexible membranes can elongate substantially before failing, and little problem is anticipated for cover FML failure in the case of cover subsidence over a large area. Locally severe subsidence, however, may produce substantial differential settlement and much greater elongation of the FML. Several investigators have shown through multidimensional stress-strain analyses that allowable strains reported by manufacturers of FMLs may be much higher than the actual strain at failure of FML's in field conditions. Manufacturers' elongation data are generally for one-dimensional strain stretch tests wherein strain is distributed evenly within the grip points of a tensile test device. In situ conditions can be expected to produce multidimensional stresses and uneven distribution of strain and cause thinning and possible tearing and premature failure of FML's.

Steffen[11] tested several geomembranes in a pressure vessel designed to stress the entire surface of a 3-foot diameter specimen of the geomembrane. He reported strains at failure of 9 percent for 90 mil HDPE and 15 percent for 80 mil HDPE, which is about 1 percent of the strain reported from manufacturers' one-dimensional stress-strain tests. (His tests on PVC, CPE, EPC, and EPDM produced higher strains, from 40 to 70+ percent.) Tests conducted on varying thicknesses of HDPE indicated that thicker FMLs were able to achieve higher strains before failing. Strong[12] showed through tests of membranes stressed over artificial fissures and hard points in a pressure cell that high localized elongations could be minimized by using thicker membranes and by incorporating a geotextile (a woven fabric) into the geomembrane application. The investigations indicate that failure of FML's in areas of severe differential settlement may occur at lower strain values than would be expected from FML manufacturers' test data. Furthermore, thicker FML's may allow greater strains to occur before failure.

Because the FML is secluded within the cover, it cannot easily be inspected and its condition determined. Every effort should be made when placing wastes in the landfill to reduce the potential for differential settlement, particularly in the upper layers where local subsidences of the cover may severely strain the FML component.

SECTION 5

MITIGATION OF SETTLEMENT AND EFFECTS OF SETTLEMENT

LANDFILL TREATMENT TO REDUCE SETTLEMENT POTENTIAL

Section 4 discussed the philosophy and theory behind controlling the amount of and total time for settlement of a hazardous waste landfill. Practices that optimize the variables of Equation 4 reduce the time to maximum settlement and make the landfill more manageable after closure. This subsection describes potential ways of treating the landfill contents to reduce and hasten ultimate settlement. Because soils and soil-like sludges and other materials constitute a major part of all hazardous waste landfills, it is not unreasonable to suggest adaptation of soil stabilization techniques to landfills. This subsection presents methods for fill compaction and waste fixation.

Fill Compaction

The following discussion makes reference to cohesive and noncohesive soils. Cohesive soils are generally those consisting of grain diameters passing the No. 200 US Standard sieve, or 0.074 millimetre (silts and clays), and coarse grained materials are those with substantial amounts of fines in the matrix such as clayey sands. Cohesionless soils are coarse grained soils such as sand and gravel, the grains of which are more free to move within the soil mass than are the grains of cohesive soils.

Standard Compaction Methods--

Standard compaction methods for soils include the use of specially designed motorized compaction equipment and laboratory and field monitoring procedures to achieve desired soil density, plasticity, and permeability. The reader is referred to the discussion of soil compaction methods and procedures regarding the application of the methods to landfill cover preparation. The same methods and equipment are applicable to compaction of some hazardous waste fills to achieve greater preclosure settlement and to lessen the potential for postclosure settlement and subsidence.

Vibrocompaction--

Vibrocompaction methods in use in civil engineering include blasting, vibrating probe, and vibratory rollers and have been used for rapid densification of saturated cohesionless soils. The range of grain-size distributions suitable for treatment by vibrocompaction is generally from coarse to fine sand (noncohesive soils). The effectiveness of the vibratory methods is greatly reduced if the percent finer than the No. 200 sieve exceeds about 20 percent or if more than about 5 percent is finer than 0.002 mm, primarily because the hydraulic conductivity of such materials is too low to prevent rapid drainage following liquefaction. Only the vibratory roller could be considered for compacting hazardous waste landfills. The other methods are considered too risky or are inappropriate for use in hazardous waste landfills.

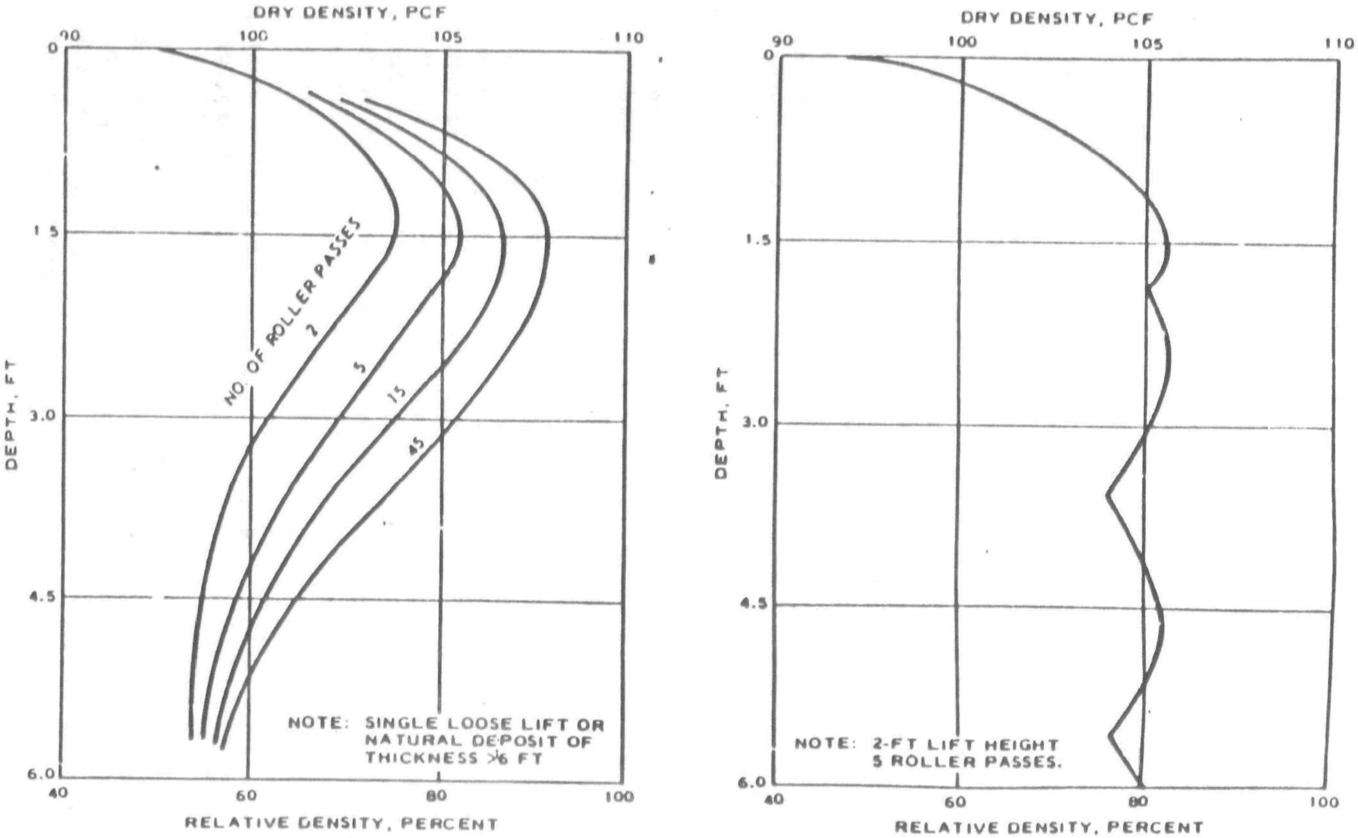
Where dry or saturated cohesionless fills are being placed, vibratory rollers are likely to be the best and most economical means for achieving high density and strength. The effective depth of densification may be 6 feet or more for the heaviest vibratory rollers (Figure 12a). For a fill placed in successive lifts, a density-depth distribution similar to that in Figure 12b results. A properly matched system of lift thickness, soil type, and roller type can yield compacted layers at a relative density of 90 percent or more (relative density is a comparison of the existing void ratio of a soil with the range of possible void ratios for the soil, and is expressed by $(e_{max} - e)/(e_{max} - e_{min})$ where e_{max} is the void ratio in its loosest state and e_{min} the void ratio in its densest state).

Precompression--

Preloading--Earth fill or other material is placed over the landfill prior to final closure in amounts sufficient to produce a stress in the soft soil equal to that anticipated from the final structures (or in the case of landfills, the final cover). As the time required for consolidation of the soft soil may be long (months to years), varying directly as the square of the layer thickness and inversely as the hydraulic conductivity, preloading alone is likely to be suitable only for stabilizing thin layers and with a long period of time available prior to final development of the site.

Surcharging--If the thickness of the fill placed for preloading is greater than that of the expected structure-induced loading (the final cover and appurtenances), the excess fill is termed a surcharge fill. The amount of consolidation varies approximately in proportion to the stress increase. The preloading fill plus surcharge can cause a given amount of settlement in shorter time than can the preloading fill alone. Thus, through the use of surcharge fills, the time required for preloading can be reduced significantly. Both primary consolidation and most of the secondary compression settlements can be taken out in advance by surcharge fills. Secondary compression settlements may be the major part of the total settlement of highly organic deposits or of old landfill sites. The landfill operator will probably have to ask the permitter for an extension of closure time to perform the surcharging.

Vertical drains--The required preloading time for most soft clay deposits more than about 10 feet thick will be large. The consolidation time may be reduced by providing a shorter drainage path by installing vertical sand drains. Sand drains are typically 10 to 15 inches in diameter and are installed at spacings of 5 to 15 feet. Perforated risers can also be used as vertical drains. Horizontal drainage layers facilitate internal drainage. As discussed previously, any system that removes leachate from within the landfill helps reduce the time to achieve maximum settlement and adds to the long range stability of the landfill.



a. DENSITY VERSUS DEPTH FOR DIFFERENT NUMBERS OF ROLLER PASSES

b. DENSITY VERSUS DEPTH RELATIONSHIP FOR A SERIES OF 2-FT LIFTS

Figure 12. Sand densification using vibratory rollers.[13]

Waste Fixation

Waste fixation describes a variety of processes by which fluid or liquid wastes are strengthened or made solid by mixing with other agents. Similar terms often used are waste solidification or waste stabilization. The two processes most commonly used by operators of hazardous waste landfills to fix wastes are absorption (or adsorption) and cementation. Some fixation processes absorb the liquid waste and make the mixture appear as a solid. The liquid may or may not be immobilized. Other processes, such as cementation, produce a chemical and physical change in the mixture and impart considerable strength relative to the original substance. Two goals of fixation are gain in compressive strength and binding or retention of liquids. Increase in compressive strength reduces compression of the waste and limits settlement of the landfill. Retention of liquids prevents the production of leachate within the landfill but if not completely effective may increase the time to ultimate consolidation.

Fly ash primarily from coal-fired power plants, kiln-dust from cement manufacture, and absorptive clays are often-used absorbents in the waste disposal industry because of their relatively low cost and availability. Some fly ashes and kiln dust have pozzolanic qualities, that is, they react with calcium hydroxide in the presence of water to form cementitious compounds. Fly ash and kiln dust serve both as an absorbent and in some cases as strengtheners when mixed with many liquid hazardous wastes. Their effectiveness as stabilizers depends both on the properties of the absorbents and of the materials being stabilized. Tests must be run on potential mixes to determine effectiveness.

Absorptive clays such as fullers earth are used in more limited quantities in landfill waste stabilization because of higher materials cost. A common use is as an additive to drums of liquid wastes to reduce the amount of free liquids entering the landfill. Adsorptive clays are rarely used in solidifying large volumes of bulk wastes, whereas fly ash and kiln dust are commonly used for that purpose. Engineering characteristics of mixtures of fly ash and absorptive clays and water and oil (simulated liquid wastes), and of real wastes treated with pozzolanic material, are presented in Section 3 of this manual.

Chemical grouts and plasticizers have been introduced to the growing waste fixation market. The long-term effectiveness of particulate additives to retain liquids within the waste under consolidation pressures and after chemical breakdown of the mixture in a landfill environment has not been determined, but is suspected.

Boutwell[14] reported on a process whereby a small quantity of a polymer is added to a waste-dust mixture to render the mix less porous by blocking the pores. Technological advances will surely be made in the field of waste fixation in the next few years and should be monitored for application to hazardous waste landfill operations.

DESIGN AND CONSTRUCTION OF COVERS TO ACCOMMODATE SUBSIDENCE

This subsection discusses considerations in designing and constructing final covers to withstand deformations resulting from settlement and subsidence.

Compaction of Cover Soils

Goals of Compaction--

The barrier soils of final landfill covers are usually compacted to achieve desired low permeability to liquids, a primary concern of hazardous waste landfills. Consideration must also be given to preserving the plasticity and flexibility of the cover soil to protect it when it is subjected to deformation. Inflexible or stiff cover soils are more likely to crack when deformed than are soils of low stiffness. The desired flexibility can be achieved by compacting the cover soils at a water content that is wet of optimum. Figure 13 is a soil's compaction curve. The curve is made up of points representing the dry densities of soils compacted at increasing water contents. The maximum density that can be achieved is represented by the peak of the curve. The water content at the peak is called the optimum water content for the soil. Any more water added to the soil will produce only lower compaction densities. Cover soils compacted wet of optimum water content are more plastic and less stiff and brittle than they would be if compacted at lower water content, and are less likely to develop zones of tensile stress than are soils compacted dry of optimum. Fortunately, soils compacted wet of optimum also exhibit low permeability, and the goals are compatible.

Standard and Modified Compaction--

The specification of compactive effort to be performed on a soil is determined from laboratory tests conducted on a sample of the soil. Two common laboratory tests are the standard Proctor and the modified compaction tests. In the standard Proctor test, samples of the soil at increasing water contents are compacted by hand in a mold using a 5.5 pound hammer falling 12 inches per blow and applying 25 blows per layer for 3 layers. The dry density of the sample after compaction at each water content is recorded and a curve like that in Figure 13 is produced. The standard Proctor test was considered to reproduce compactive efforts similar to those of compaction equipment in use when the test was developed. Compaction specifications were made based on a percentage of the maximum density achieved in the Proctor test (say 90, 95, or 100 percent of standard Proctor).

Some projects required higher compaction efforts. A modified compaction test was developed using greater laboratory compaction effort. The modified test uses a 10 pound hammer falling 18 inches per blow, with 25 blows applied to each of 5 layers. A job specification of 95 percent modified compaction would then produce an in-place soil of higher density than one compacted at 95 percent of standard Proctor.

Compaction specifications further indicate the water content relative to optimum at which the soil should be compacted, because soils have different characteristics at water contents above, at, or below the optimum water content (Figure 13). Clays compacted on the wet side of the optimum water content are less permeable than those compacted on the dry side. Clays compacted

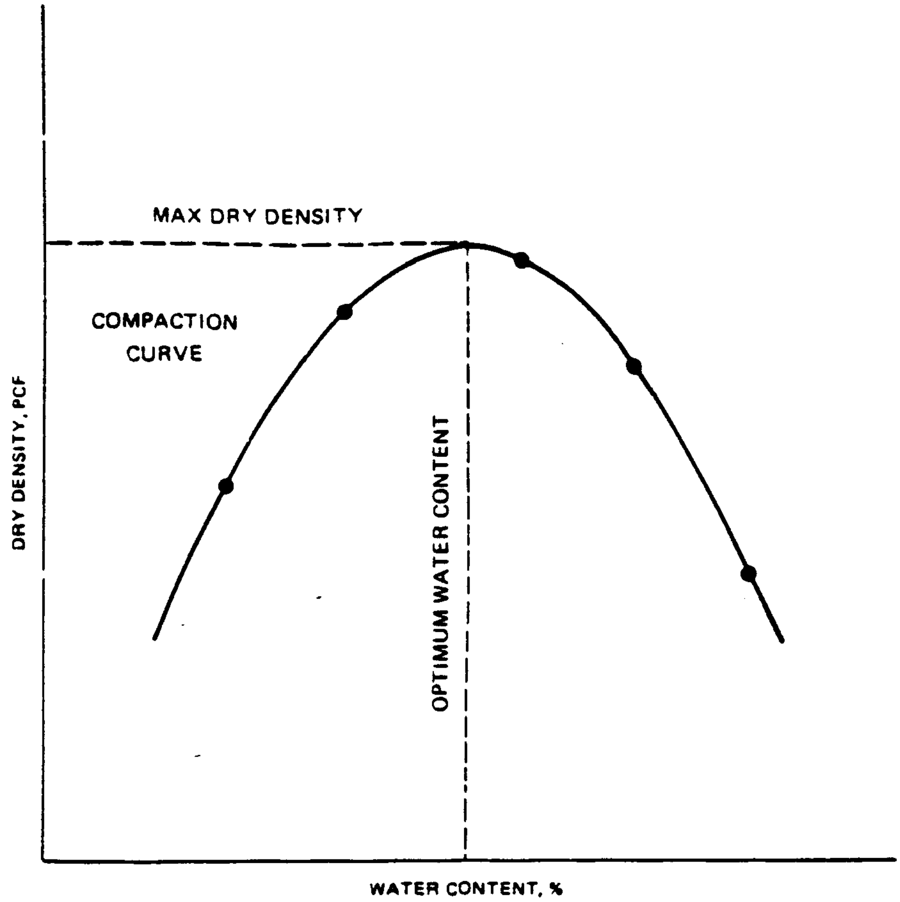


Figure 13. Soil compaction curve. Each point on the curve represents a sample of the soil compacted to a particular dry density at a given water content.

wet of optimum are more compressible at low stresses and less compressible at high stresses than are clays compacted dry of optimum. Clays compacted dry of optimum are stronger and have a higher stress-strain modulus than do clays compacted wet of optimum. Because the characteristics desired in clays of the covers of landfills are primarily low permeability and low stiffness, compaction of cover clays should logically be specified at lower compaction effort at wet of optimum (generally not to exceed 3 percent wet of optimum).

Control of the compaction effort of soils in the field consists of conducting in-place or laboratory tests to determine the field density and water content of the soil after compaction to assure compliance with specifications. Soils that are too loose require additional compaction effort which can be accomplished by increasing the weight of ballast or the number of passes of the compacting unit or by reducing the thickness of the spread layer. Compaction effort can also be increased by using heavier or different types of equipment.

If the water content of the soil is above the desired value, it can be reduced by aerating the soil through scarifying or tilling. If the water content is too low, water can be added to the fill and distributed or mixed with the soil in the borrow area.

Soils of the final covers of hazardous waste landfills require special precautions and considerations. Care must be exercised in placing soils over an FML to prevent damage to the FML. A buffer layer of granular material like sand should be placed over the FML to protect it (see Figure 2). The in-place density and water content of the compacted soil should be carefully checked to ensure compliance with compaction specifications. If subsidence or differential settlement of the cover is expected or predicted, the soil portion of the cover should be flexible and of low stiffness to withstand the deformations.

Compaction Equipment--

The principal types of compacting equipment are the smooth wheel roller, the rubber-tired roller, the sheepsfoot roller, and the vibratory compactor. Vibratory rollers are the least effective compactors for cohesive soils, the kind of soil used in the barrier portion of landfill covers. Rubber-tired rollers with high tire pressures and sheepsfoot rollers are effective for cohesive soils. Sheepsfoot rollers are particularly effective at bonding of lifts during compaction of cohesive soils. Footed rollers were in use at several RCRA landfills inspected in a previous investigation[3]. Table 4 summarizes the capabilities and characteristics of compaction equipment.

Compaction Characteristics of Soils--

Suitability of soils for embankments is similar to that for fill covers because the desired characteristics for both applications include accommodation of deformations and low permeability. The clay-rich soils (SC, CL, and CH) yield the lowest permeabilities and highest plasticities when compacted and are the soil types commonly used to construct the soil barrier portion of landfill covers. Reference 16 discusses soil types and compaction characteristics.

TABLE 4. COMPACTION EQUIPMENT AND METHODS

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
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	Soil Type — Foot Contact Area, in.² (cm²) — Foot Contact Pressures, psi (MPa): Fine-grained soil PI > 30 — 5-12 (32-77) — 250-500 (1.7-3.4) Fine-grained soil PI < 30 — 7-14 (45-90) — 200-400 (1.4-2.8) Coarse-grained soil — 10-14 (64-90) — 150-250 (1.0-1.7) Efficient compaction of wet soils requires less contact pressures than the same soils at lower moisture contents	For earth dam, highway, and airfield work, drum of 60-in. dia. (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 0.75-1.75 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 shearing the soil on the third or fourth pass
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 18,000-25,000 lb (80-111 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 40-50 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 wobble-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. (3.6-5.6 kN lineal cm) of width of real 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 10-20 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 (40-53 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 1,600 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

(Continued)

TABLE 4. (Concluded)

Equipment Type	Applicability	Requirements for Compaction of 95 to 100 Percent Standard Proctor, Maximum Density			Possible Variations in Equipment
		Compacted Lift Thickness, in. (cm)	Passes or Coverages	Dimensions and Weight of Equipment	
Crawler tractor	Best suited for coarse-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-graded 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 4-10 in. (1.57-1.93 cm)

Source: Haxo, H., Jr. et al., 1980. "Lining of Waste Impoundment and Disposal Facilities," EPA Report No. EPA/530/SW-870, Sep.

Other Construction Considerations

The RCRA hazardous waste landfill cover is made up of layers which include materials other than the soil barrier, as illustrated in Figure 2. This subsection discusses considerations in the design and construction of the cover as a layered unit, following the basic component arrangement shown in Figure 2.

Suitability of Various Soils as Covers--

Lutton et al.[17] evaluated and ranked soils for their performance as landfill covers. Table 5 lists the rankings for selected performance characteristics. Rankings are 1 (best) through 13 (poorest). Since this report concerns itself with the soil barrier portion of the cover of a hazardous waste landfill, some of the characteristics in Table 5 are not directly applicable. Soils with fines in the matrix and clay soils perform well in impeding percolation of water and migration of gases (columns A and B). Erosion control (column C) is not a primary consideration for the barrier portion because the barrier is not normally exposed.

Rankings for column D (crack resistance) are based on expansion and contraction with accompanying cracking controlled by the clay mineralogy of the soils. Fine grained and clayey soils accordingly rank low in resistance to that kind of cracking. Final cover barrier ~~soils,~~ however, are covered immediately after emplacement and are not allowed to undergo change in water content. Cracking by expansion/contraction is not normally a problem. From the standpoint of resistance to cracking during deformation from settlement and subsidence, the clay soils rank high, as discussed in earlier sections. If the cover layers overlying the barrier portion are compromised, and the clay portion is exposed to the atmosphere, drying or water infiltration can occur, and the barrier may well be subject to cracking by desiccation and shrinkage as suggested in column D of Table 5. The table might best be used as a guide to selection of other layers that make up the cover and less to evaluate soils for the construction of the cover soil barrier.

Use of Soil Additives and Soil Stabilization--

Where appropriate soils for use as cover are not available on site, it may be necessary to bring in clay rich soils or to add bentonite (a swelling clay) to available soils to achieve the desired characteristics of low permeability and plasticity in the cover. Table 6 presents recommended application rates for sodium bentonite to reduce permeability of soils in farm ponds. It can be used to estimate the amount of bentonite required for soils of landfill covers. The use of soil stabilization techniques such as addition of lime or pozzolanic materials or grouts is not anticipated to be of use in cover soils because the techniques tend to great~~ly~~ stiffen the treated soils, an undesired quality in landfill covers.

CORRECTIVE ACTION FOR SUBSIDENCE

Corrective actions for subsidence events in a hazardous waste landfill are beyond the scope of this report, but some points are worthy of mention.

Cover damage caused by subsidence will require repair and will likely require correction of the cause. Damage is expected to be corrected by

TABLE 5. RANKING OF USCS SOIL TYPES BY PERFORMANCE OF COVER FUNCTIONS[13]

Soil Type	Column A Impede Water Circulation	Column B Impede Gas Migration	Column C Water Erosion Control	Column D Crack Resistance[(2)]	Column E Reduce Frost Heave
GW	10	10	1	1	1
GP	12	9	1	1	1
GM	7	7	4	3	4
GC	5	4	3	5	7
SW	9	8	2	1	2
SP	11	7	2	1	2
SM	8	6	6	2	5
SC	6	5	7	4	6
ML	4	3	13	6	10
CL	2	2	12	8	8
OL	--	--	11	7	8
MH	3	--	10	9	9
CH	1	1	9	10	3
OH	--	--	8	9	--
Pt	--	--	5	--	--

TABLE 6. SOIL CONSERVATION SERVICES 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

excavation and exposure of the barrier layer, removal of the damaged part, refilling of the underlying foundation, and replacement of the barrier layer.

Correction of the cause of subsidence may require increasing the strength of the underlying waste materials. Of the measures expected to be applicable, grout injection to increase the compressive strength may be the most cost-effective. However, various methods of deep compaction may also be applicable, such as vibrocompaction, vibrodisplacement compaction, and heavy tamping. Excavation and replacement of the waste itself is not a feasible measure at this time.

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TABLE A-1. CHARACTERISTICS OF SELECTED HAZARDOUS WASTE LANDFILLS*

Site No.	Type	Construction	Landfill Surface Dimensions	Landfill Surface Area	Depth/ Thickness	Interior Side Slopes (V on H)	Subgrade Materials	Depth to Water Table	Liner Specs (Ascending Order)
1	Excavated pit	Single cell	300 × 300 ft	2 ac	100 ft	Near vert (80-85°)	Calcareous claystone	>100 ft	2 ft on base, 8 ft on sides, compacted clay
2	Cut and fill, diked valley	Single cell	NA**	3 ac	10 to 100 ft (irregular topography)	1 on 1	Clay shale, siltstone, sandstone	No known aquifers	Minimum 2 ft of remolded clay shale
3	Cut and fill, diked valley	Multicell	1,100 × 300 ft (largest landfill)	~5 ac	85 ft max (irregular topography)	1 on 1	Diatomaceous shale and claystone	No known aquifers	Unlined: in-place rock serves as barrier (land is excavated to fresh rock)
4	Combination pit and above-grade fill	NA	NA	26 ac	25 ft below grade	NA	Glacial till (clay)	NA	No liner; relies on in place clays (10 ft in-place clay required)
5	Excavated pit	Multicell	1,000 × 700 ft (irregular)	15 ac	Total 70 to 85 ft, 55 to 70 ft below grade	1 on 2	Glacial till (clay)	NA	10 ft remolded or in-place clay, 80 mil HDPE, 1 ft compacted clay buffer (10 ft in-place clay required)
6	Excavated pit with partial embankment	Single cell	~375 × 940 ft	8 ac	40 ft below grade	1 on 3	Glacial till (clay)	120-150 ft	Min. 10 ft in-place clay, 80 mil HDPE (10 ft in-place clay required)
7	Excavated pit	Multicell	~2,600 × 600 ft (rectangular)	37 ac	34 ft below grade	1 on 3	Lacustrine sand, silt, clay, and glacial till	NA	Varies: older portions clay-lined, newer w/60 mil HDPE and geotextile (10 ft in-place clay required)

(Continued)

* All references cited in the appendixes can be found in the references at the end of main text.
** Not applicable.

TABLE A-1. (Continued)

Site No.	Leachate Collection System	Final Cover Spec (Ascending Order)	Final Cover Slope	Waste Forms	Other Wastes	Waste Layer Thickness	Waste Stabilization Processes or Additives	Handling of Liquids	Intermediate Cover	Year Constructed (Status)
1	8 in. washed gravel blanket on base, slopes 5% to PVC pipe on one side, to 4 ft concrete riser in sump	8 ft clay compacted in 1-ft lifts to 95% standard Proctor	Not specified (center to be crowned)	Bulk stabilized and drums, drums on sides	Plastic drums, steel tanks, wood pallets	2 ft	Absorbents for liquids	Absorbents (cement kiln dust and crushed claystone) mixed w/liquids in bulk and in drums	12 to 18 in. of crushed claystone	~1979 (Active)
2	French drains along inside toe of slope, to 18 in. steel riser in sump at barrier dam	Final cover not designed (1983)	NA	Bulk stabilized liquids and sludges	Steel and fiber drums, polluted soil (no intact drums)	1 ft	Bulk wastes mixed with clay shale, spread in layers	Liquids mixed with clay shale to consistency of soil	None	1979 (Active 1983)
3	Gravity drainage to perf. PVC pipe at toe of dike, to gravel sump and steel riser	Final cover not designed (1983)	NA	Drums of stabilized wastes (drums on-end)	Wood crates of contaminated soil; transformers	~3 ft	NA	Liquids are stabilized in the drums by the waste supplier	4 ft crushed diatomaceous shale	1978 (Active 1983)
4	Fill base slopes 1% to gravel bed at lower end	NA	NA	Drums, debris, bulk liquids, solids	Numerous and varied	NA	None	Liquids mixed with other waste at toe of working face	~6 in. daily cover (nominal)	Late 1976 (Active)
5	4-in. HDPE pipe in 6 in. gravel + 6 in. sand drainage blanket, on geotextile. Slope to 4 ft concrete riser in sump, in each cell	2 ft compacted clay, HDPE, 1-1/2 ft uncompacted soil, 6 in. topsoil	10%	Drums and bulk waste (drums on-end)	Numerous	~3 ft	Neutralization of acids w/lime	Free liquids pretreated	6 in. native clay soils (+ lime in acids cell)	U.C.
6	Five, slotted 6-in. PVC pipe in 2 ft of sand, slope to 4 ft riser in 20 × 20 × 8 ft sump	7 ft thick: random fill, drainage layer, impervious layer, pervious layer, 3 ft topsoil, geotextile, topsoil	NA	Drums and bulk waste	Numerous	2-1/2 to 3 ft	Fly ash and arc dust formerly mixed w/liquids	Free liquids, if detected, are rejected by facility	6 in. daily cover of local soil and/or sludges	U.C.
7	6-in. pipe in 3-ft diam trench of crushed stone, in 1 ft granular drainage blanket	2 ft compacted clay, synthetic membrane, 1 ft drainage blanket, 2 ft topsoil	NA	Open head drums, bulk solids	Numerous	NA	Limestone flue dust mixed w/acids	Liquid wastes are dewatered, filter cake landfilled	1 to 2 ft daily cover of local soil and sludge	~1975 (Active)

(Continued)

TABLE A-1. (Continued)

Site No.	Type	Construction	Landfill Surface Dimensions	Landfill Surface Area	Depth/ Thickness	Interior Side Slopes (V on H)	Subgrade Materials	Depth to Water Table	Liner Specs (Ascending Order)
8	Excavated trenches	Single cell (multiple trenches)	540 × 240 ft each trench	18 ac of trenches (total)	Total 40 ft, 20 ft below grade	1 on 2 1/2	Glacial till (clay)	~30 ft	2 ft compacted clay, 60 mil HDPE, 150 mil geotextile (10 ft in-place clay required)
9	Excavated pit	Multicell	450 × 300 ft (rectangular)	~3 ac	Total 47 ft, 25 ft below grade	1 on 2	Glacial till (clay), some sand	6-25 ft (perched)	6-in. compacted clay, 80 mil HDPE, 1-2 ft compacted clay buffer (5 ft in-place clay required)
10	Excavated pits	Single cell (multiple pits)	20 × 20 ft pits	17.9 ac of haz. waste pits	15 ft (below grade)	Vertical	Glacial till (stiff silty clay)	60 to 100 ft	None
11	Diked surface impoundment	Multicell	~900 × 930 × 1,300 × 520 ft (not rectangular)	15 ac, in 3 cells of 5 ac each	67 ft max	1 on 2 to 1 on 3	Sandy silt w/ clay lenses	~2 to 9 ft	Area 1-single layer, 30 mil Hypalon. Area 2-double layer, 30 mil Hypalon with sand between. Area 3-double layer, Hypalon w/gravel and "Typar" geotextile between
12	Excavated pit	Multicell	540 × 540 ft	7 ac	50 ft	Near vert.	Interbed gravelly silt and clay and volcanic ash	375 ft (nonpotable)	Unlined
13	Combination pit and diked impoundment	Multicell	NA	12 ac	40 ft	1 on 1	Glacial till (clay)	NA	10 ft remolded clay, 80 mil HDPE, 2 ft compacted clay

(Continued)

(Sheet 3 of 10)

TABLE A-1. (Continued)

Site No.	Leachate Collection System	Final Cover Space (Ascending Order)	Final Cover Slope	Waste Forms	Other Wastes	Waste Layer Thickness	Waste Stabilization Processes or Additives	Handling of Liquids	Intermediate Cover	Year Constructed (Status)
8	4-in. perf. PVC each side of trench in 1 ft drainage blanket, 2% grade to 4 ft floors	2 ft compacted clay, synthetic memb., geotextile, 2 ft topsoil	10 to 33%	Drums (on-end)	NA	3 ft	NA	NA	6 in. to 1 ft limestone screenings	NA (Active)
9	8-in. clay pipe in 1-ft sand layer, slope to concrete floor in corner of each cell	1 ft soil, 20-mil HDPE, 2-ft compacted clay, 6 in. topsoil	5 to 8%	Drums and bulk waste (drums on-end)	Contaminated soil, sludges, waste debris	3 to 6 ft (1 to 2 drums/layer)	Absorbents for liquid wastes	Liquids in drums treated in drums. Bulk liquids treated in active landfill. Absorbent clays used.	6 in. soil	1982 (Active)
10	None	3-1/2 ft clay soil, compacted, 6-in. topsoil	NA	Drums and bulk waste	NA	NA	NA	No free liquid in drums	6 in. daily cover of soil	1975 (Industrial waste) (Active)
11	Areas 2, 3-12-in. gravel layer on 2% slope to two 6-in. drain pipes to 8-in. collector pipe at low end in sump	2 ft SC/CL clay soil, 1 ft topsoil. (Sides of impoundment have 1.5 ft clay soil w/1 ft topsoil)	Min. 5%	Bulk sludge at 40% solids. Drums placed in 1, 2, or 3 drum layers or in trenches	Drums, debris, lab packs, gas cylinders, freon tank cars	First lift, 11 ft, successive lifts, 8 ft, drums in trenches. Areas 2, 3 will use layers of drums, 2 per lift	NA	NA	1 ft of sludge	1975 (Area 1) 1978 (Area 2) Area 1 closed, Area 2 active
12	None (high evaporation rate)	5 ft remolded clayey soil (3 ft at edge and 5 ft at center)	1%	Drums of solidified wastes (drums on-sides)	Wood boxes, transformer cases, contaminated soil	4 to 6 ft, variable	Absorbents for liquids	Mixed in drums w/bentonite, fuller's earth, kiln dust	6 in. native soils	1970 (Active 1983)
13	Graded granular filter blanket, 1 ft thick, slopes 2% to concrete floor. Granular material also between drums	3 ft clay buffer, HDPE, 1-1/2 ft clay, 6-in. topsoil	8%	Steel and plastic drums (drums on-end)	Fiber drums, plastic bags	3 ft	Specialized additives and cover for specific wastes (clay, limestone, ashes, lime, slag, sludge)	Liquids solidified inside drums	6 to 12 in. selected materials	NA (Active 1983)

(Continued)

TABLE A-1. (Continued)

Site No.	Type	Construction	Landfill Surface Dimensions	Landfill Surface Area	Depth/ Thickness	Interior Side Slopes (V on H)	Subgrade Materials	Depth to Water Table	Liner Specs (Ascending Order)
14	Old quarry pit	NA	NA	3.85 ac	40 ft	1 on 3	Sand, gravel	NA	Two 4-in. bentonite layers, leachate system between
15	Combination: pit and diked impoundment	Multicell	380 × 730 ft	6 ac, 25 ac dedicated	~49 ft, max, (15 ft below ground)	1 on 2	Glacial till and lacustrine clay	Piezometric surface 0 to 10 ft	In-place clay, Hypalon, 80-mil HDPE, 1 ft clay, geotextile, 1 ft gravel
16	Combination: pit and diked impoundment	Multicell	552 × 552 ft total pit	7 ac	41 ft max (18 ft below ground)	1 on 2	Glacial till and lacustrine clay	Piezometric surface 0 to 10 ft	2 ft reworked in-place clay, 30-mil Hypalon, 2 ft of clay
17	Diked surface impoundment	Multicell	400 × 900 ft and 350 × 700 ft (contiguous cells)	~16 ac	NA	1 on 2	Silty sand, gravel, some clay	2.5 to 22 ft	Single bentonite and soil mixture (3 lb bentonite mixed into top 4 in. of soil, compacted)
18	Old quarry pit, diked at one end	Multicell	NA	4.6 ac	~35 ft	Near vert.	Limestone	NA	Compacted silty, clayey loam
19	Old quarry pit	NA	NA	18 ac	Max 45 ft	Near vert.	NA	NA	4 in. subbase material, 2 in. asphalt
20	Excavated pit	Multicell	500 × 600	9 ac	40 ft	1 on 3	Siliceous claystone	Piezometric surface 30 to 40 ft	5 ft compacted clay, 30-mil Hypalon synthetic, 2 ft buffer of sandy soil

(Continued)

TABLE A-1. (Continued)

Site No.	Leachate Collection System	Final Cover Spec. (Ascending Order)	Final Cover Slope	Waste Forms	Other Wastes	Waste Layer Thickness	Waste Stabilization Processes or Additives	Handling of Liquids	Intermediate Cover	Year Constructed (Status)
14	6-in. layer of sand, gravel between liners, 4-in. drain pipe to concrete riser @ 1/8 in./ft	Composite; 3-1/2 ft. 12 in. gravel on last waste layer, 6 in. soil + bentonite, 24 in. topsoil	NA	Bulk, 30 to 35% solids (sludge)	NA	NA	NA	No free liquids on site	None	1976 (Active)
15	Network of 4 to 6-in. slotted PVC in 12-in. crushed stone blanket on liner. Also perm. requirements for succeeding interm. cover soils	3-ft compacted clay, synthetic liner, 1-1/2 ft uncompacted clay, 6-in. topsoil planned	8%	Steel drums (on-end) and bulk	NA	~3 ft	Lime added to some wastes	Max. 10% free liquid (1 in. standing liquid) in drums	12-18 in. of bulk waste. Cover soils must have at least 10^{-4} cm/sec permeability	1975 (Area 1) 1978 (Area 2) (Area 1 closed, Area 2 active)
16	Each cell, floor slopes 1% to 8-in. vitrified clay collection pipes at inside toe, to 24-in. standpipe	3 ft compacted clay, 20-mil PVC, 18-in. uncompacted clay, 6-in. topsoil	8%	Drums and bulk (drums on-end)	NA	~3 ft	Lime added to some wastes	Drums spot-checked. Same as SCA No. 11	6-in. bulk waste. Cover soils must have at least 10^{-4} cm/sec permeability	1979 (Closed)
17	4-in. perforated PVC pipe in 12-in. gravel blanket, slope to sump	2 ft of clay, 6-in. flow zone, 12-in. topsoil	2-4%	Bulk sludge	None	2.5 ft	Waste sludge treated with lime, mixed with fill soils	Sludge dewatered in lagoon	6 in. of native soils	NA (Active)
18	NA	2 ft silt or clay-loam compacted to 95% of "maximum density," and 1 ft sandy soil	2-6%	Bulk sludge, 20-30% solids	Minor debris (scrap metal, rags, bricks, soil, plastic)	Irregular 2-4 ft (?)	Fly ash and/or kiln dust sometimes mixed with the sludge	No liquid waste permitted, but sludges may have up to 80% liquid	NA	Early 198 (Active)
19	Underdrain beneath liner	Clay, asphalt, topsoil proposed	NA	Bulk, treated sludges	NA	Spread in "thin" layers	Lime and fly ash mixed w/ waste	No liquids permitted	None	Early 19 (Closed)
20	Radial network of 4-in. PVC in 2 ft of sandy soil, drains to 4-ft concrete riser at center of cell	1 ft sandy clay buffer, 20 mil Hypalon, 2 ft remolded sandy clay, 18 in. topsoil	5%	Bulk stabilized and drums, drums on-end	Plastic drums, wood pallets, sheet plastic	~3 ft	Absorbents for liquids	Absorbents (crushed claystone mixed w/ liquids in bulk and drums)	2 ft crushed native claystone	1978 (Active 1983)

(Continued)

TABLE A-1. (Continued)

Site No.	Type	Construction	Landfill Surface Dimensions	Landfill Surface Area	Depth/ Thickness	Interior Side Slopes (V on H)	Subgrade Materials	Depth to Water Table	Liner System (Ascending Order)
21	Excavated pit	Multicell	NA	3 to 5 ac each cell	50 ft	1 on 2.5	Clay, silty clay, silty sand	NA	4-ft remolded clay compacted in 6-in. lifts
22	Excavated trenches	Single-cell (multiple trenches)	200 × 170 ft (one trench)	1 ac	15 ft	1 on 1.5	Clay, silty clay, silty sand	Piezometric surface at 2-3 ft	4 ft of in-place or 3 ft of remolded clay-rich soil
23	Excavated trenches	Single-cell (multiple trenches)	100 × 500 ft (one trench)	1 ac	12-17 ft	1 on 1	Silty clay over fine silty sand	Piezometric surface at 2-3 ft	4 ft of in-place clay-rich soil
24	Excavated pit (trench)	Single-cell (multiple trenches)	175 × 300 ft	>1 ac	22 ft	1 on 1	Clay, sandy clay, silty sand	Piezometric surface 30 ft	4 ft of in-place or 3 ft of remolded clay rich soil
25	Excavated pit	Single cell	700 × 400 ft	6.5 ac	32 ft	1 on 3	Silts, sand. Thick clay at base	5 ft	Layer of gravel layer of sand (leak detection 5 ft of clay compacted in 6-in. lifts, 80 mil HDPE, thin layer of clay (buffer). Bentonite slurry wall around cell
26	NA	Trenches or cells	235 × 116 ft, typical cell or trench	NA	5 ft	NA	NA	NA	Not lined
27	NA	Trenches or cells	1,350 × 300 ft, typical cell or trench	NA	40 ft	NA	NA	NA	Natural (in-place) clay
28	NA	Trenches or cells	1,000 × 125 ft, typical	NA	15 ft	NA	NA	NA	Recompacted clay
29	NA	Trenches or cells	1,700 × 200 ft, typical	NA	50 ft	NA	NA	NA	Natural clay, drain layer

(Continued)

(Sheet 3 of 10)

TABLE A-1. (Continued)

Site No.	Leachate Collection System	Final Cover Specs (Ascending Order)	Final Cover Slope	Waste Forms	Other Wastes	Waste Layer Thickness	Waste Stabilization Processes or Additives	Handling of Liquids	Intermediate Cover	Year Constructed (Status)
21	6-in. PVC pipe every 100 ft on sides and bottom of pit, in 6 in. of gravel	None planned (expansion to above-ground impoundment is planned)	NA	Bulk, stabilized liquids and bulk solids	Steel drums (drums stacked 3-deep where present)	1/2 to 1 ft lifts of bulk waste	Absorbents for liquids	Cement kiln dust mixed w/ liquids	2-3 ft of bulk solid waste between drum layers (minor)	NA (Active 1983)
22	6-in. pea gravel blanket on base of trench, 6-in. PVC at center of trench slopes to concrete riser	4 ft of compacted clay-rich soil	NA	Bulk stabilized liquids and solid waste	Plastic, wood, various containers, crushed drums	~15 ft (end dumped on steep face)	NA	Liquids mixed w/native soil and spread into fill	None	1980 (Active 1983)
23	4-in. slotted PVC pipe on centerline, base of trench in limited crushed rock blanket	4 ft of compacted clay	2%	Bulk stabilized liquids and solid waste	Crushed drums	~1 ft	Absorbents for liquids	Bulk liquids mixed w/cement kiln dust or fly ash in pit, then moved to landfill	None	1980 (Active 1983)
24	Slotted PVC riser	4 ft of compacted clay-rich soil	2-5%	Drums of stabilized wastes (drums on-edge)	Bulk wastes	NA	NA	Liquids stabilized by mixing w/in-place soils	NA	1972 (Active 1983)
25	Laterals of perforated PVC pipe every 50 ft along cell base. Sump and riser each side. PVC wrapped with geotextile as filter	5 ft compacted clay, 30 mil synthetic liner, 6-12 ft clayey soil, 6-in. top soil, grassed	2%	Bulk stabilized, debris, drums	Waste soil, debris	2 ft lifts. Waste layers advanced across cell on benches	All wastes solidified before disposition	Liquids are pretreated, mixing pits with cement kiln dust or fly ash	12-18 in. of soil or bulk waste	1984
26	None	NA	20% planned	Bulk waste	NA	NA	NA	NA	17 in.	~1974
27	Drainpipe in gravel and sand	Recompacted clay, topsoil	2%	Drums of solid waste, bulk waste	Empty drums	NA	NA	Visual inspection. Liquids decanted from drums	None	~1980
28	Drainpipe in gravel w/ geotextile, sumps	NA	2%	Bulk waste	NA	NA	NA	NA	12 in., soil	1980
29	Drainpipe in gravel, sand, w/sump	Recompacted clay, PVC membrane, drain layer, recompacted clay, topsoil	NA	Drums of solid waste, bulk waste	NA	NA	NA	Drums sampled. Liquids rejected	6 in., soil	~1980

(Continued)

(Sheet 8 of 10)

TABLE A-1. (Continued)

Site No.	Type	Construction	Landfill Surface Dimensions	Landfill Surface Area	Depth/ Thickness	Interior Side Slopes (V on H)	Subgrade Materials	Depth to Water Table	Liner Specs (Ascending Order)
30	NA	NA	NA	NA	NA	NA	NA	NA	Unspecified layer, recompacted clay, drain layer, recompacted clay, drain layer
31	NA	Single-cell	Individual lifts 180 × 130 ft typical	NA	13 ft	NA	NA	NA	Recompacted clay, drain layer, recompacted clay, unspecified layer
32	NA	Trenches or cells	190 × 150 ft typical	NA	13 ft	NA	NA	NA	None
33	NA	Single-cell	NA	NA	NA	NA	NA	NA	Drain layer, recompacted clay
34	NA	Single-cell	500 × 300 ft typical lift	NA	10 ft	NA	NA	NA	Unspecified liner (no synthetic liner)
35	NA	Single-cell	NA	NA	NA	NA	NA	NA	Natural (in-place) clay, recompacted clay

(Continued)

TABLE A-1. (Concluded)

Site No.	Leachate Collection System	Final Cover Space (Ascending Order)	Final Cover Slope	Waste Forms	Other Wastes	Waste Layer Thickness	Waste Stabilization Processes or Additives	Handling of Liquids	Intermediate Cover	Year Constructed (Status)
30	Drainpipe in sand, w/geotextile, w/ sumps	NA	1%	Bulk waste	NA	NA	NA	NA	NA	~1977
31	Drainpipe on 20-ft centers, in gravel w/sumps	NA	3%	Bulk waste	NA	NA	NA	NA	12-in. non-soil	~1976
32	None	Recompacted clay, unspecified layer, topsoil	2%	Bulk waste	Na	NA	NA	NA	8 in. soil	~1980
33	Drainpipe in sand, no sump	NA	2%	Bulk waste	NA	NA	NA	NA	NA	~1980
34	Drainpipe on 600-ft centers, in gravel, w/sumps	Compacted clay, unspecified layer, topsoil	30%	Bulk waste (wastes removed from drums and landfilled)	NA	NA	NA	NA	9-in. soil	~1975
35	Drainpipe in sand and gravel, w/sump	NA	2%	Bulk and drums	NA	NA	NA	Drums are spot-checked for liquids	NA	~1972

APPENDIX B

CLASSIFICATION OF GEOMEMBRANES (reprinted from Proceedings, International Conference on Geomembranes, Denver, Colo., June 20-24, 1984)

Geomembrane:

Synthetic membranes, polymeric membranes, flexible membrane liners, plastic liners, and impervious sheets are a few examples of the many names given to these relatively new materials. Although many users of these materials often prefer to use trade names, this practice is deemed inappropriate because it creates considerable confusion.

Geomembrane is the generic term proposed to identify these liner and barrier materials. Geomembranes are impermeable membrane liners and barriers used in civil engineering for geotechnical projects. They can be either sprayed on a surface or prefabricated and transported to the construction site. Sprayed-on geomembranes are composed predominantly of asphalt. They are either sprayed directly on a surface (earth, concrete, etc.) or onto a geotextile. Prefabricated geomembranes are usually composed of synthetic polymers, elastomers (rubbers), or plastomers (plastics); some are reinforced with a fabric. There are also prefabricated asphaltic geomembranes.

Classification of Geomembranes[1]

Geomembranes can be classified according to production process and reinforcement:

1. Made in situ, non-reinforced geomembranes are made by spraying or otherwise placing a hot or cold viscous material directly onto the surface to be lined (earth, concrete, etc.). The non-reinforced geomembranes made by spraying are called "sprayed-on (or spray-applied, or sprayed in situ) non-reinforced geomembranes." Typical materials used are based on asphalt, asphalt-elastomer compound, or polymers such as polyurethane. Due to the spray application, the final thickness of such geomembranes is not easy to control and may vary significantly from one location to another. Typically, required thicknesses range between 3 and 7.5 mm (120 and 300 mils).

2. Made in situ, reinforced geomembranes are made by spraying or otherwise placing a hot or cold viscous material onto a fabric. The reinforced geomembranes made by spraying are called "sprayed-on (or spray-applied, or sprayed in situ) reinforced geomembranes." Typical materials used are the same as for the made in situ non-reinforced geomembranes described above. Typical fabrics used are the needle-punched nonwoven geotextiles because they can absorb viscous materials. As discussed above, the final thickness of such geomembranes is not easy to control. Typically, required thicknesses range between 3 and 7.5 mm (120 and 300 mils).

[1] Giroud, J. P. and Frobel, R. K. "Geomembrane Products" *Geotechnical Fabrics Report*, Vol I, number 2 (1983).

3. Manufactured, non-reinforced geomembranes are made in a plant by extrusion or calendering of a polymeric compound, without any fabric reinforcement, or by spreading a polymer on a sheet of paper removed at the end of the manufacturing process. Typical thicknesses range from 0.25 to 4 mm (10 to 160 mils) for geomembranes made by extrusion and 0.25 to 2 mm (10 to 80 mils) for geomembranes made by calendering. Typical roll width for geomembranes made by extrusion is 5 to 10 m (16 to 33 ft), although some are narrower. Typical roll width for geomembranes made by calendering is 1.5 m (5 ft), with some manufacturers producing 1.8 to 2.4 m (6 to 8 ft) wide rolls.

4. Manufactured, reinforced geomembranes are made in a plant, usually by spread coating or calendering. In spread-coated geomembranes, the reinforcing fabric (woven or nonwoven) is impregnated and coated on one or both sides with the compound, either polymeric or asphaltic. In calendered reinforced geomembranes, the reinforcing fabric is usually a scrim. Calendered geomembranes are always made with polymeric compounds and are usually made us of three plies: compound/scrim/compound. Sometimes they are made of five plies: compound/scrim/compound/scrim/compound. Geomembranes with additional plies can be made on a custom basis. Typical thicknesses of asphaltic spread-coated geomembranes are 3 to 10 mm (1/8 to 3/8 inch). Typical thicknesses for polymeric spread-coated and three-ply calendered geomembranes are 0.75 to 1.5 mm (30 to 60 mils). Typical thicknesses for five-ply calendered geomembranes are 1 to 1.5 mm (40 to 60 mils).

5. Manufactured reinforced geomembranes laminated with a fabric are made by calendering a manufactured geomembrane (usually a non-reinforced geomembrane previously made by calendering or extrusion) with a fabric (usually a nonwoven) which remains apparent on one face of the final product.

Classification of Geomembrane Polymers
(National Sanitation Foundation):

1. *Thermoplastics*: Polyvinyl Chloride (PVC); Oil Resistant PVC (PVC-OR); Thermoplastic Nitrile-PVC (TN-PVC); Ethylene Interpolymer Alloy (EIA);

2. *Cristalline Thermoplastics*: Low Density Polyethylene (LDPE); High Density Polyethylene (HDPE); High Density Polyethylene-Alloy (HDPE-A); Polypropylene; Elasticized Polyolefin;

3. *Thermoplastic Elastomers*: Chlorinated Polyethylen (CPE); Chlorinated Polyethylene-Alloy (CPE-A); Chlorosulfonated Polyethylene (CSPE), also commonly referred to as "Hypalon;" Thermoplastic Ethylene-Propylene Diene Monomer (T-EPDM);

4. *Elastomers*: Isoprene--Isobutylene Rubber (IIR), also commonly referred to as Butyl Rubber; Ethylene-Propylene Diene Monomer (EPDM); Polychloroprene (CR), also commonly referred to as "Neoprene;" Epichlorohydrin Rubber (CO).

APPENDIX C

FIELD EXPERIMENTAL EXAMPLE OF SETTLEMENT ANALYSIS BY STANDARD CONSOLIDATION THEORY

RETAINING STRUCTURES AND FILL PLACEMENT

An experimental paper-mill sludge landfill was constructed and monitored for a 2-year period to obtain engineering information essential to developing procedures for the design and operation of pulp and paper-mill waste landfills.* The landfill site was an old gravel pit. The experimental fill consisted of two sludge layers, initially 10 feet thick, with 1-foot-thick sand drainage blankets at the top, middle, and bottom. An earth dike provided lateral confinement of the sludge, and a surcharge load consisting of 3 feet of natural soil was used. A lysimeter study provided information on changes in quality of the leachate when passed through selected natural soils. Figures C-1 and C-2 show the landfill in a plan view and typical cross section, respectively.

SLUDGE MATERIAL

The dewatered sludge used in the landfill had the physical properties shown in Table C-1. The Consistency Limits are the water contents at the liquid and plastic limits, respectively. These properties were determined from samples taken at various elevations as the sludge was placed. Therefore, the properties represent the initial, as-placed sludge conditions.

CONSOLIDATION AND SETTLEMENT

Figures C-3 and C-4 give the initial average effective stress, $P'_o = 138$ pound/foot^2 for each 10-foot-thick layer. The total load acting on the lower sludge layer, ΔP_{lower}, is calculated as follows:

Weight of sludge (design thickness) above lower layer $= 10$ ft $\times 70$ lb/ft^3 $= 700$ lb/ft^2

Top sand layer weight $= 1$ ft $\times 100$ lb/ft^3 $= 100$ lb/ft^2

Surcharge weight $= 3$ ft $\times 130$ lb/ft^3 $= 390$ lb/ft^2

$\Delta P_{lower} = (700 + 100 + 390)$ lb/ft^2 $= 1{,}190$ lb/ft^2

Average effective stress $P'_{lower} = P'_o + \Delta P_{lower} = (138 + 1{,}190)$ lb/ft^2 $= 1{,}328$ lb/ft^2 $= 0.664$ ton/ft^2 ≈ 0.64 kg/cm^2

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* From Ledbetter, Richard H., "Design Considerations for Pulp and Paper-Mill Sludge Landfills," EPA 600/3-76-111, December, 1976.

The total load acting on the upper layer, ΔP_{upper} , is the weight of the sand blanket and surcharge. The sand blanket weight is included in P'_o . Therefore, ΔP_{upper} = 3 ft × 130 lb/foot^3 = 390 lb/foot^2 = surcharge weight . The average effective stress is $P'_{upper} = P'_o + \Delta P_{upper}$ = (138 + 390) lb/foot^2 = 528 lb/foot^2 = 0.264 ton/foot^2 0.264 kg/cm^2.

Figure C-5 shows the consolidation characteristics for the sludge used in the experimental landfill. Using the settlement equation

$$\Delta H_{pri} = \frac{C_c H_t}{1 + e_o} \left(\log_{10} \frac{P'_o + \Delta P}{P'_o} \right) \qquad \text{(C-1)}$$

the primary settlement for each layer can be calculated as follows:

Lower layer properties.

$$C_c = 1.65$$

$$H_t = 10 \text{ ft}$$

$$e_o = 4.85 \text{ at } P'_o$$

$$P'_o = 138 \text{ lb/ft}^2$$

$$\Delta P_{lower} = 1190 \text{ lb/ft}^2$$

$$\Delta H_{pri_{lower}} = \frac{(1.65)(10 \text{ ft})}{1 + 4.85} \left(\log_{10} \frac{1328 \text{ lb/ft}^2}{138 \text{ lb/ft}^2} \right)$$

$$= 2.82 \text{ ft} \times 0.9833$$

$$= 2.77 \text{ ft} = 33.28 \text{ in.}$$

Upper layer properties.

$$C_c = 1.65$$

$$H_t = 10 \text{ ft}$$

$$e_o = 4.85 \text{ at } P'_o$$

$$P'_o = 138 \text{ lb/ft}^2$$

$$\Delta P_{upper} = 390 \text{ lb/ft}^2$$

$$\Delta H_{pri_{upper}} = \frac{(1.65)(10\ ft)}{1 + 4.85} \log_{10}\left(\frac{528\ lb/ft^2}{138\ lb/ft^2}\right)$$

$$= 2.82\ ft \times 0.582$$

$$= 1.64\ ft = 19.72\ in.$$

Secondary settlement, defined as

$$\Delta H_{sec} = C_a H_t \left(\log_{10} \frac{t_{sec}}{t_{pri}}\right)$$

where C_a = coefficient of secondary compression, from lab
t_{sec} = time for which settlement is significant
t_{pri} = time to completion of 100 percent primary consolidation.

can be calculated as follows:

Lower layer C_a = 0.018 from Figure C-5 laboratory tests corresponding to

$$P'_{lower} = 0.664\ ton/ft^2$$

$$H_t = 10\ ft$$

For one cycle of log time

$$\Delta H_{sec_{lower}} = C_a H_t$$

$$= 0.018 \times 10\ ft = 0.18\ ft$$

$$= 2.16\ in.$$

Upper layer C_a = 0.016 from Figure C-5 laboratory tests corresponding to

$$P'_{upper} = 0.264\ ton/ft^2.$$

$$H_t = 10\ ft$$

For one cycle of log time

$$\Delta H_{sec_{upper}} = C_a H_t$$

$$= 0.016 \times 10\ ft = 0.16\ ft$$

$$= 1.92\ in.$$

Total settlement for the landfill is calculated as follows:

Lower layer $\Delta H_{total_{lower}} = \Delta H_{pri} + \Delta H_{sec} = 33.28$ in. + 2.16 in.

$= 35.44$ in.

Upper layer $\Delta H_{total_{upper}} = 19.72$ in. + 1.92 in. = 21.64 in.

Total for the landfill

$$\Delta H_{total} = \Delta H_{total_{lower}} + \Delta H_{total_{upper}}$$

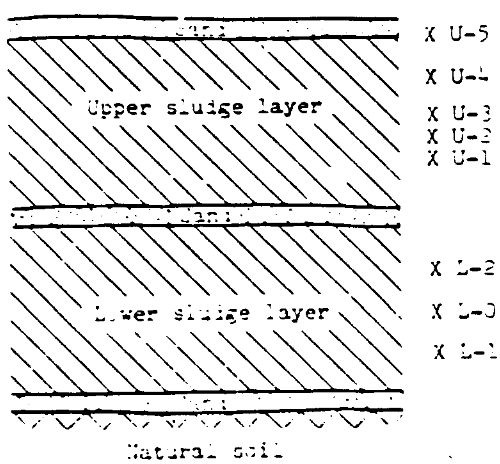
$$= 35.44 \text{ in.} + 21.64 \text{ in.} = 57.08 \text{ in.} = 4.76 \text{ ft}$$

TABLE C-1. PHYSICAL PROPERTIES OF PAPER-MILL SLUDGE

Sludge Sample		Consistency Limits (LL-PL)	Ash Content percent	Solids Content, Percent by Weight	Specific Gravity of Solids
No.	Elevation in Layer ft				
L-0	5	325.4-141.6	35.7	28.5	2.01
L-1*	2.5	257.3-102.7	42.2	27.2	2.05
L-2*	7.5	247.7-105.6	43.3	28.2	2.07
U-1**	2.5	184.5- 86.0	59.4	34.4	2.24
U-2**	4	218.5-101.6	46.5	31.9	2.07
U-3**	5	297.5-133.0	36.5	26.9	1.91
U-4**	7.5	287.4-122.1	34.2	29.0	1.87
U-5**	10	302.8-138.6	32.2	28.4	1.92

* Average of three samples.
** Average of three tests per sample location.
Sludge unit weight as placed, $\gamma_m \approx 70$ pcf.
Soil surcharge unit weight, $\gamma_m \approx 130.4$ pcf.
Laboratory test sample locations.

Laboratory test sample locations.



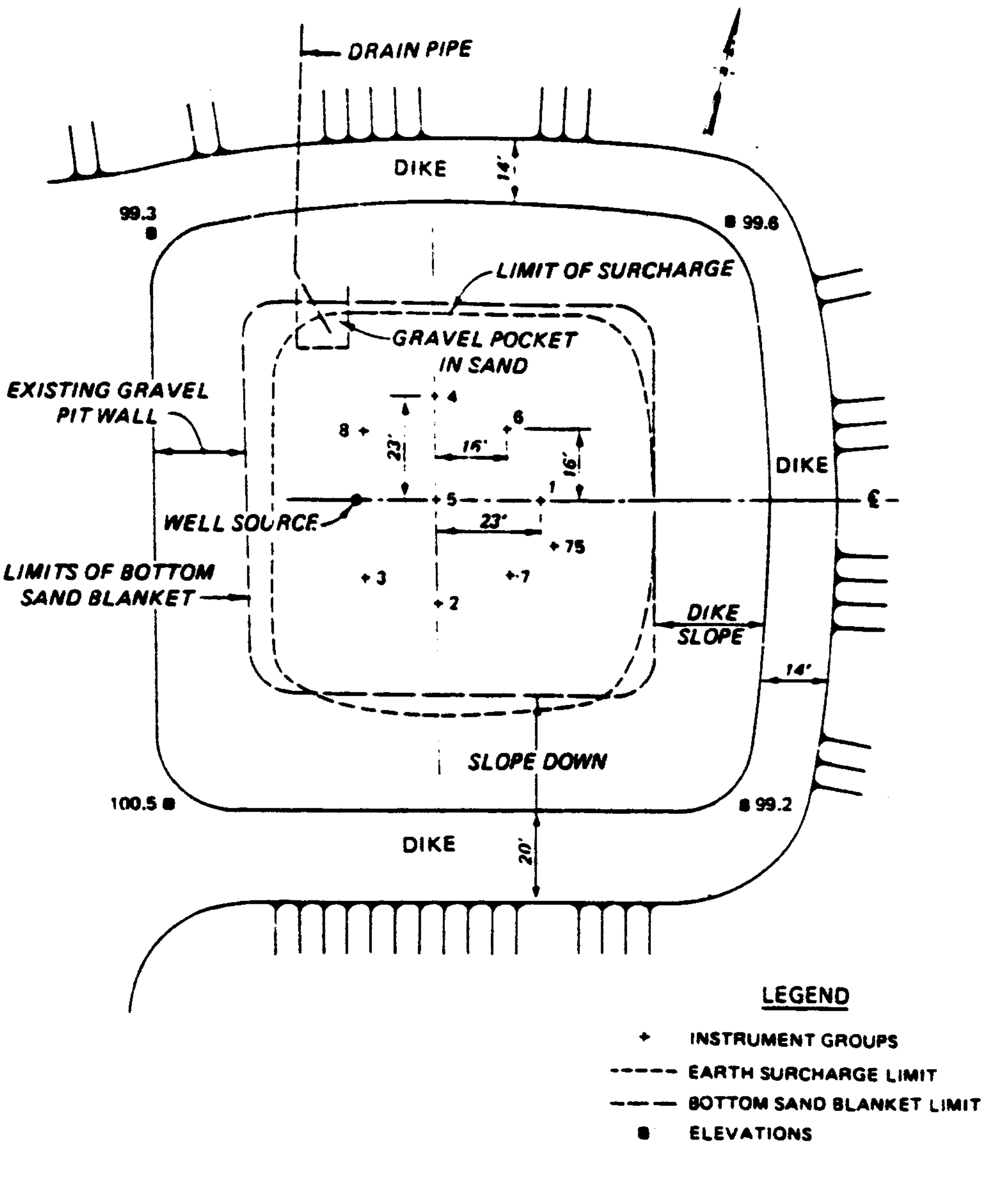


Figure C-1. Experimental landfill, plan view.

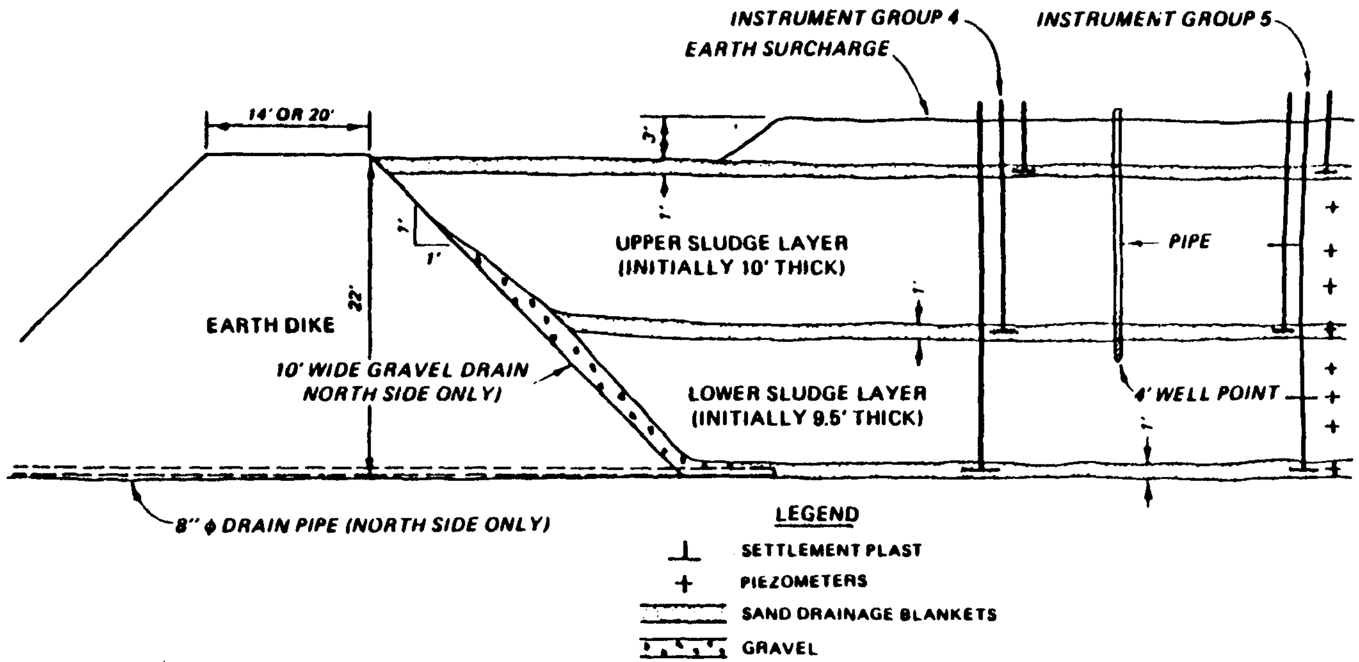


Figure C-2. Typical cross section of experimental landfill.

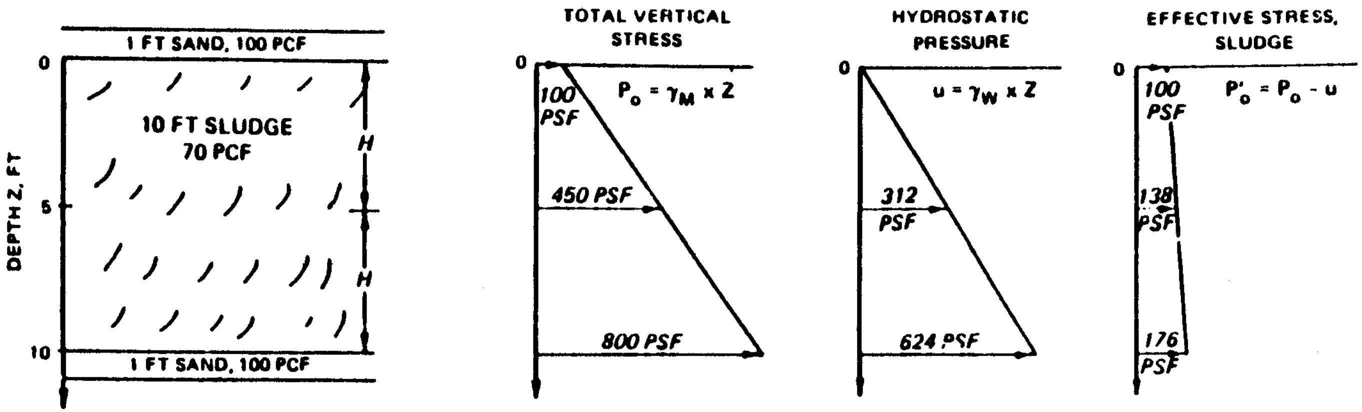


Figure C-3. Load-depth diagram.

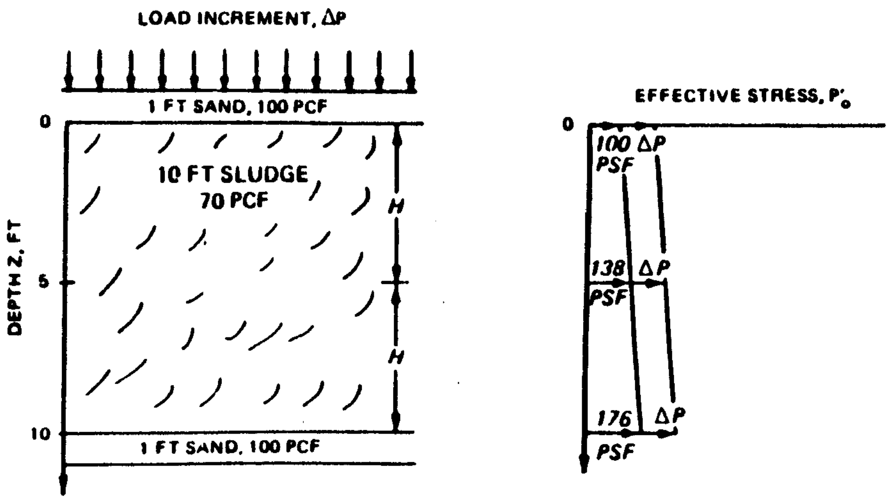


Figure C-4. Load increment added to a sludge layer.

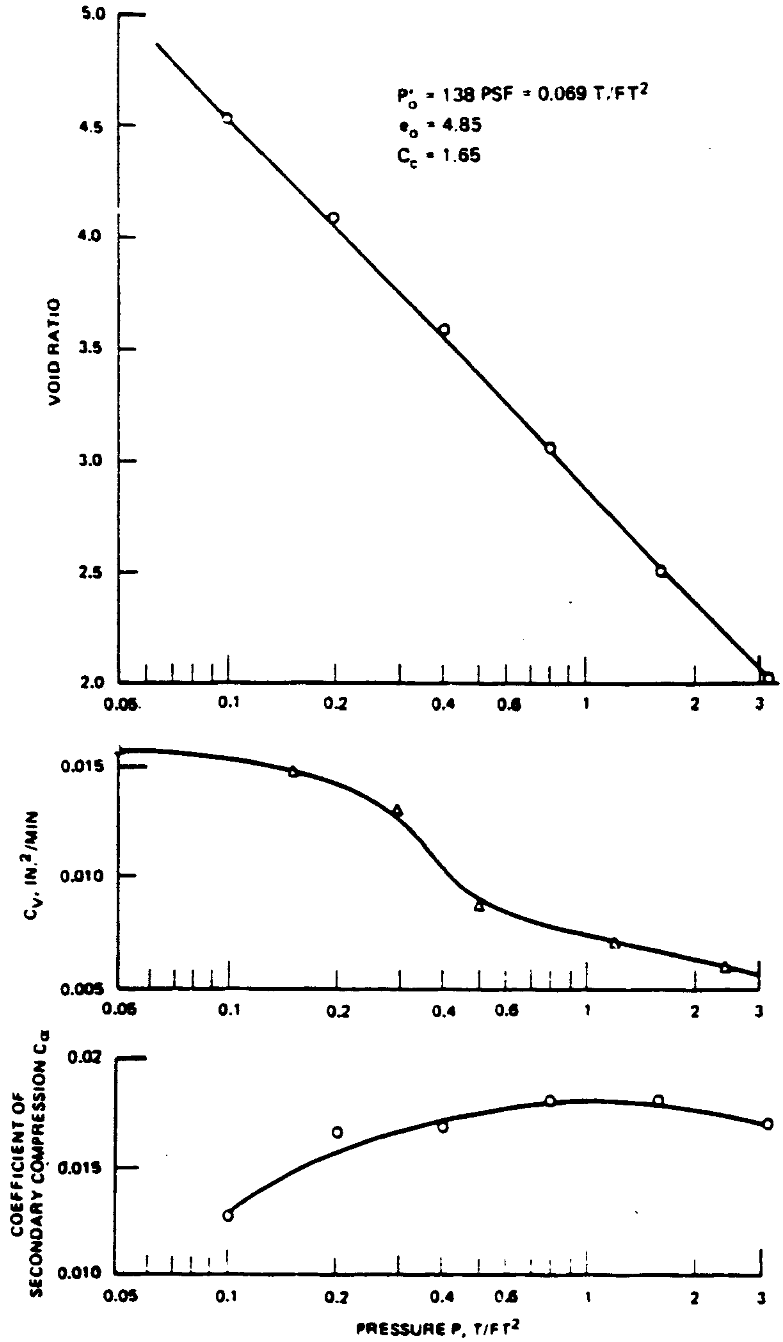


Figure C-5. Consolidation characteristics of sample sludges.

APPENDIX D

CONSOLIDATION EQUATION

The consolidation equation may be expressed as

$$t = \frac{THc^2}{Cv} \qquad \text{(D-1)}$$

where

t = time required for consolidation
T = a dimensionless time factor
Hc = length of the longest drainage path
Cv = coefficients of consolidation

The coefficient of consolidation may be expressed in the form

$$Cv = k \frac{(1 + e)}{a_v \gamma w} \qquad \text{(D-2)}$$

where

k = coefficient of permeability of the soil medium
e = void ratio of the soil medium
$a_v = \frac{-de}{dp}$, negative slope of the void ratio versus pressure relationship for the soil in question

Substituting Equation D-2 into Equation D-1,

$$t = -\frac{TH_c^2 \left(\frac{de}{dp}\right) \gamma w}{k(1 + e)} \qquad \text{(D-3)}$$

Differentiating the well known weight volume equation

$$e = \frac{G_s \gamma w}{\gamma d} - 1 \qquad \text{(D-4)}$$

where

G_s = specific gravity of the soil solids
γd = dry density of the soil

yields

$$de = -G_s \gamma w \frac{d\gamma d}{\gamma d^2} \qquad \text{(D-5)}$$

Finally substituting Equations D-4 and D-5 into Equation D-3 gives