

A TALE OF TWO CONDITIONS: HEAP LEACH PAD VERSUS LANDFILL LINER STRENGTHS

Allan J. Breitenbach, P.E.
Vector Engineering, Golden, Colorado USA

Richard S. Thiel, P.E.
Vector Engineering, Grass Valley, California USA

ABSTRACT

Heap leach pad and solid waste landfill facilities are among the largest manmade fill structures in the world. A unique attribute of these structures is that they are often founded on a geomembrane liner system, which can potentially compromise their slope stability. One of the most important aspects of these fill structures for stable exterior fill slope conditions is the interface strength of the underlying geomembrane liner system, as related to the construction and operation of the facilities.

The interface of the geomembrane liner in contact with the underlying and overlying soil or synthetic materials generally results in a planar low-strength condition at the more critical downhill toe limits of the fill structures. This planar liner interface strength is generally less than the strength of the stored containment fill materials above the liner system, as well as the subgrade foundation materials beneath the liner system.

This paper presents an overview of the general similarities and differences in heap leach pad versus solid waste landfill liner designs and operations with respect to liner strength conditions and the development of stable slope conditions over the life of the facilities.

INTRODUCTION

Geomembrane lined leach pads (in the mining industry) and landfill structures (in the solid waste disposal industry) have three basic components related to the stability of the exterior fill slopes. These components include the underlying subgrade materials, the base liner system, and the overlying containment fill materials. A geomembrane lined heap leach pad operation is shown on Figure 1. A geomembrane lined landfill operation is shown on Figure 2.

The prepared subgrade materials beneath the lined structures vary from site to site and require site-specific engineering requirements for stable excavations, site-grading fills, and underdrain systems that are generally common to both the leach pad and landfill structures. Therefore, the subgrade foundation conditions, which relate to the global stability of the structures, are not included in this discussion.

This paper will present a slope stability overview and description of typical containment fill construction above the liner system for both the heap leach pads and solid waste landfills, followed by a discussion of how the general design and operational approaches for these two

different structures affect the base liner strength conditions. Unlined, single clay lined and single geomembrane lined heap and landfill structures are excluded from this discussion.

STATIC AND SEISMIC SLOPE STABILITY PERFORMANCE OVERVIEW

The historic slope stability performance of geomembrane-lined fill structures mainly concerns the more critical downhill side of the exterior containment fill slopes. The past slope failures on geomembrane-lined fill structures have shown that slides generally occur at the planar geomembrane liner interface contact with either the underliner or overliner materials. The most common failure interfaces are between the composite geomembrane and underlying low-permeability soil liner layer, and with the geocomposite underlying GCL or overlying synthetic geotextile and geocomposite drainage materials.

One of the earliest and most known slope failures in the containment industry was the Kettleman Hills landfill slope failure in Northern California in 1988 (Mitchell et al., 1990; Stark and Poepfel, 1992). Several other major landfill slope failures occurred between 1988 and 1997 in North America, Europe, Africa, and South America (Koerner and Soong, 1999; Stark et al., 1998; Brink et al., 1999).

The most known leach pad liner failure in the mining industry is Summitville in Southern Colorado. Although no known heap stack slope failures occurred at Summitville, there was a possibility that the exposed pad liner may have been damaged by an avalanche debris slide movement into the lined pad area during early stacking operations. Several less known leach pad heap slope failures occurred between 1985 and 1993 at mine sites in North America, South America and Australia (Breitenbach, 1997).

The Northridge earthquake in Southern California in 1994 (Matasovic et al., 1995) and subsequent earthquakes in Chile and Peru from 1995 to the present day have given some insight into the seismic behavior and stability of high fills on geomembrane liner systems. The only known leach pad heap failure from an earthquake event occurred on a copper heap in Southern Peru in June 2001 with a 2 m actively leached top crushed and a agglomerated ore lift liquefying on an interlift liner at 10 m above the base pad liner system (Earthquake Spectra, 2003). The earthquake was estimated at a magnitude 8.4 M with peak ground accelerations at about 0.22 g in bedrock at the base of the heap. The worst earthquake damage reported for a landfill was at the Chiquita Canyon landfill during the Northridge earthquake (Matasovic et al., 1995). Only minor soil cracking at the slope crests and one 50 ft (15 m) tear occurred in the geomembrane at the crest, where a destructive sample had been patched. No known earthquake induced slope failures have occurred to date on the base liner systems beneath leach pad heaps and solid waste landfills.

The historic performance of static fill slope failures on geomembrane liner systems indicates that translational (lateral movement) wedge slip failures generally occur along the planar composite liner interface contact with clayey soils or geocomposite liner interface contact with geosynthetic materials. However, heap leach slope failures generally differ from solid waste landfill slope failures in that the slope failure generally occurs during the initial or re-heap lift placement operations, rather than at the higher fill lift heights (Breitenbach, 1997; Smith and Giroud, 2000). The only exceptions for high fill slope failures on liners include either weak

foundation conditions beneath the lined facility or excessive hydraulic conditions within the containment materials above the liner system. Most landfill failures have occurred at an interim fill condition (versus final fill grades) during operations, because the waste fill had been placed either too high and/or too steep for the interim conditions.

CONTAINMENT FILL CONSTRUCTION

General

The containment fill materials for leach pads and municipal solid waste (MSW) landfills have several significant strength differences related to fill types, densities, heights, exterior slope geometry, hydraulic conditions, and construction fill placement operations. These differences have a direct influence on the slope stability conditions during construction, operation, and closure of the facilities. The typical containment fill construction for gold, silver, and some copper heap leach pads and for solid waste landfills are described below and summarized in Tables 1 and 2.

Table 1 - Summary Comparison of Operational Conditions (above base geocomposite or composite liner system)

Structure Feature	Heap Leach Pads	Solid Waste Landfills
Documented static bottom liner failures?	Yes - but less frequent after the initial containment fill lift placement.	Yes - most frequent during interim containment fill conditions.
Documented seismic interface stability failures?	None for base liner. One case of interlift liner liquefaction from 8.4 M earthquake, 0.22g.	None. Some minor surface material slumping and liner tears.
When failure is most likely to occur?	Initial ore heap lift placement operations before leaching.	Interim operations where fill gets too high and steep relative to base conditions; excessive leachate injection.
Liquid added during filling operations?	Yes - continuous active heap leaching by drip emitter or sprinkler irrigation wetting on the top containment fill lift surface.	Historically no; now it is common (bioreactors). Liquid added in manners ranging from spraying on active face to injection in wells.
Internal liquid drainage on base liner to sump leachate collection?	Generally no - bottom gravity drainage to external ditch and process ponds common; valley leaching to internal ponds not common.	Generally yes - bottom gravity drainage to internal sump most common.
Anticipated hydraulic head buildup on base liner? How much?	Fully drained granular or agglomerated ore fills with less than 2 ft of average head typical at base; hydraulic head buildup prevents effective oxidation and leaching of ore.	Supposedly less than one foot head at base - suspect may be 10's of feet with clogged LCRS's, with multiple perched leachate zones.

Structure Feature	Heap Leach Pads	Solid Waste Landfills
Hydraulic conductivity of drain cover fill over base liner?	10 times more pervious than the overlying ore heap fill in addition to drain pipes.	1×10^{-2} cm/s or more per regulations up to 10 cm/s in addition to drain pipes.
Hydraulic conductivity of containment fill?	Typical bottom range at 1×10^{-3} to 1×10^{-4} cm/s or higher for fully drained leaching conditions. Some long term degradation possible with copper ore acid leaching to less than 1×10^{-5} cm/s.	Typical range 1×10^{-3} to 1×10^{-7} cm/s. Age, type and depth have significant influence.
Rate of containment fill rise?	Most rapid in first year of operations with 20 to 40 ft/yr typical on average.	Individual cells may rise at a rate of 10 to 100 ft/yr, with 50 ft/yr typical.
Settlement of containment fill?	Yes - 7 to 10 % typical for gold and silver heap fills and 10 to 15 % for copper and zinc heap fills; rapid primary consolidation occurs with each additional ore lift load on fully drained loose lift granular fills.	Yes - waste decomposition leads to substantial settlement over time.
Life of fill operations?	Typically 5 years with 10 years for expansion pads.	Individual cells typically 1 to 3 years; typical facility lifetime is 30 to 100 years.

Table 2 - Summary Comparison of Design and Construction Conditions
(above base geocomposite or composite liner system)

Structure Feature	Heap Leach Pads	Solid Waste Landfills
Typical exterior containment fill slope angle?	Angle-of-repose lifts with setback benches for 2H:1V overall slope most common.	Generally ranges from 2H:1V to 4H:1V; 3H:1V overall slope most common.
Typical base liner grades at downhill toe?	1 to 3 % with no toe berm support most common.	Generally 1 to 10 % with toe berm support. Toe berm heights from 5 ft to 100 ft.
Typical containment fill heights?	100 to 200 ft with maximum heights of 500 ft.	50 to 300 ft common (200 ft typical); max heights up to 500 ft.
Typical containment fill lift thickness?	15 to 30 ft high lifts with 5% or flatter top fill surface grades for ease in stacking.	15 to 30 ft high lifts.
Typical fill lift material type?	Crushed and agglomerated sands and gravels or run of mine rock fill with gravel to cobble and boulder sized rock fragments.	Municipal solid waste with highly varying composition of residential and industrial materials including putrescibles, wood, metal, plastic, soil & etc.

Structure Feature	Heap Leach Pads	Solid Waste Landfills
Containment fill lift compaction?	No - dumped dry and loose lifts with surface loosened by dozer with ripper for solution leaching.	Yes - usually compacted in 3 ft thick layers either on 3H:1V slope or horizontal.
Type of base liner design?	Composite liner most common – CCL or GCL with overlying GM. Single GM or unlined subgrade common in copper heaps.	Geocomposite liner most common – CCL or GCL with overlying GM. Double liners with leak detection common.
Composite soil liner placement condition?	CCL typically compacted at or dry of optimum moisture content to meet 1×10^{-6} cm/sec or less operational permeability with lift load.	CCL typically compacted at or wet of optimum moisture content to meet 1×10^{-7} cm/sec or less permeability.
Additional liners above the base liner system within the containment fill?	Generally no - some interlift liners for copper and zinc heap leaching; raincoat surface cover liners for wet season operations.	Generally no - sloping waste fill placement and interim covers often create impermeable barrier layers within the containment fill.
Drainage layer on top of base liner?	Yes – typically, crushed free draining minus 1 inch ore or drain fill with no synthetic cushion; supplemented by drain pipes.	Yes - typically rounded sand or fine gravel or geocomposite layer with geotextile cushion for crushed rock; supplemented by drain pipes.
Downhill toe berm or excavated cell in ground?	Typically no - external gravity drainage to lined process ponds.	Typically yes - internal gravity drainage to sumps for monitoring or recirculation in fill.
Containment fill density?	Typical moist unit weight density of about 120 pcf; rapid densification in top loose lift from controlled leaching and subsequent ore lift loading and rewetting.	Typical moist unit weight density of about 75 pcf; varies significantly with depth.
Containment fill shear strength?	Varies with relative density at effective stress conditions in granular ore fill of about 36 to 40° peak friction angle and no cohesion.	Bilinear envelope: above eff. stress of 500 psf use 33° friction angle with no cohesion; below normal eff. stress of 500 psf use zero friction and 500 psf cohesion.

Structure Feature	Heap Leach Pads	Solid Waste Landfills
Base liner interface strengths?	Typical range of 16 to 22° friction angle and no adhesion typical for underliner / GM / overliner interface at peak and post-peak strength; post-peak strength for GCL or other geotextile interface is less, but not commonly used in leach pad construction. GCL as low as 6° residual.	Peak strength could be governed by GM / clay interface, if high PI clay is used (e.g. 19° peak, and post-peak governed by undrained shear strength); geotextile interfaces are common resulting in peak strength with textured GM of about 25° and post-peak 12 to 14° friction angle.
Current practice for static Factor of Safety (FS) conditions?	Static FS = 1.3 for low hazard structure with no internal ponds. Static FS = 1.5 for structure with internal ponds.	Typical static FS = 1.5 using peak strengths, and static FS > 1.1 for large-displacement strengths.
Current practice for seismic FS conditions?	Use historical records and maximum magnitude events or active fault rupture in close proximity to site with PGA factored by 50 % typical for pseudo-static slope stability analyses (COE, 1984). Pseudo-static FS > 1.1 for low hazard structures with no internal ponds, and FS > 1.2 for structures with internal ponds (valley heap leach pads).	Use 10 % chance in 250 years, which has an annual recurrence probability of about 1 in 2500 years. Pseudo static screening performed by using 75 % of peak bedrock accelerations and look for FS > 1.0. If this fails perform simplified deformation analysis and look for less than 4 to 36 inch allowable deformation on bottom liner in literature, with 12 inch most common.

Leach Pad Ore Heap Fill Construction

The construction of heap fills involves the placement of precious or base metal ore materials in controlled individual loose and relatively dry fill lifts stacked at the natural angle-of-repose. The heap ore lifts are typically stacked at 15 to 30 feet (5 to 10 meters) in thickness by haul trucks or conveyor stackers and leached to typical multiple lift maximum heights in the range of 100 to 200 feet (30 to 60 meters). The highest heap stacks to date exceed 500 feet (150 meters) above the geomembrane lined pad foundation. A geomembrane lined leach pad with a stacked and leached ore heap in the background is shown on Figure 1. The individual ore lifts are offset with benches along the exterior slope, as required for establishing the overall stable design slopes for operations. A schematic section of the exterior ore heap slope is shown on Figure 3.

Each ore lift surface is wetted uniformly during leaching by using irrigation drip emitters or sprinkler sprays. Leaching is generally conducted in 30 to 120 day or longer leach cycles with barren or recirculated alkaline (gold and silver) or acidic (copper and zinc) process solutions. The ore heap is designed to remain fully drained throughout leaching operations with a drain

system constructed at the base of the ore heap above the pad liner system. A typical leach pad drip emitter system to provide controlled leaching is shown in Figure 4.

The maximum rock size for the granular ore materials typically range from large run-of-mine cobble and boulder rock fragments to fine crushed sand and gravel particles. The crushed ore operations may include agglomeration as needed to provide a more efficient distribution of fines (minus No. 200 sieve size material) for improved permeability and recovery of the target metals.

Landfill Solid Waste Fill Construction

Municipal solid waste landfills are typically filled by compacted 1 m thick layers of waste and advancing 5 to 10 meter thick lifts across a given cell. The waste is usually end-dumped directly from trucks, or entire truck loads are dumped from tippers. The dump face at the top of the lift can range in slope from nearly flat to nearly vertical (yes, 10 meter high vertical dump faces are not uncommon). Solid waste is often covered with 0.15 m of soil cover at the end of each working day. Areas that may remain inactive for more than a few weeks may receive 0.5 m of interim cover soils. These cover soils, in addition to the gravel-covered tipping decks, often inhibit the free flow of liquids and gases through the waste mass.

In the last 5 to 10 years the addition of water, or recirculation of leachate, has become more popular. Benefits of leachate recirculation include accelerated settlement, high effective waste densities, accelerated waste degradation and gas generation, leachate disposal, and some level of leachate treatment. Observed problems include increased odor, formation of side-slope seeps, accelerated clogging of the leachate collection gravel, and flooding of gas wells and gas collection main lines. Various design and operational remedies have been suggested to ameliorate the problems caused by leachate recirculation (Thiel, 2005). Spray-recirculation of leachate on a landfill is illustrated in Figure 5.

An additional potential problem is the potential long-term concern of slope instability caused by liquid head build-up within the waste mass and clogging of the leachate collection layer (Thiel and Christie, 2005). Indicators of leachate head buildup within a landfill include side-slope seeps, encounters of elevated liquid levels when drilling vertical gas wells, and increased volume of liquid in the leak detection system. A dramatic case history of a landfill failure caused by excessive injection of leachate has been documented (Hendron et al., 1999). This problem directly impacts the issue being discussed in this paper, which is slope stability above the bottom base liner system.

BASE LINER AND DRAIN CONSTRUCTION

General

The typical base liner system for both leach pads and landfills have two common components, which include a composite clayey soil or geosynthetic clay liner contact with the geomembrane base liner, and an overlying drain cover fill. The base liner system for leach pads and solid waste landfills differ mainly by the number of liner layers constructed and the location

of the liner layer is beneath and within the containment fill. The typical composite and geocomposite liner systems for heap leach pads and solid waste landfills are described below and shown on Figures 6 and 7. The non-composite or unlined ore heaps and landfills are excluded from this discussion.

The composite and geocomposite liner systems that utilize a low permeability clayey soil in contact with the geomembrane liner are state-of-the-practice as the most practical and environmentally effective impervious barriers for hydraulic containment beneath fill structures. The liner design most widely used in the construction of leach pads and solid waste landfills includes two basic components: 1) a low permeability compacted clayey soil (CCL) or geosynthetic bentonite clay liner (GCL) placed on a prepared foundation subgrade; and 2) an impervious geomembrane liner placed in direct contact with the underlying CCL or GCL layer. A third component is generally included to minimize the hydraulic head on the liner system, which includes a base liner drain cover filter placed above the geomembrane liner and supplemented with drain pipes for gravity drainage of leachate solutions to ponds or to low-lying sump pump systems.

Occasionally a geotextile (geofabric) protective layer is placed between the overlying gravel and the geomembrane (more common in landfills than leach pads), and sometimes a geocomposite (geodrain) drainage layer is used in lieu of a gravel drain layer (again, more common for landfills than leach pads). Figure 8 illustrates gravel drain layer placement above a geomembrane liner for a heap leach pad. The construction figure for a municipal solid waste (MSW) landfill would typically be identical, except that it is common to have a geotextile cushion between the gravel and geomembrane. Also, for landfill construction, small size dozer equipment is typically specified for the gravel spreading operations because the layer thickness is typically only 0.3 m, whereas for leach pads the layer thickness is typically two or three times this amount for conventional mine equipment placement.

Leach Pad Composite Liner Construction

Lined leach pads are generally constructed with gravity solution flow to exterior collection ditches and ponds on a single composite liner system for both on/off and permanent leach pads. A geocomposite liner with synthetics are seldom used under heap leach fills and are more common in the external double-lined leach pad collection ditches and process ponds. Note that this exterior drainage design configuration generally results in no additional structural fill for toe support, since the liner system drains at-grade to a perimeter solution collection ditch with a heap slope setback distance of a few meters away from the toe ditch. This is in contrast to landfills, which typically have either a toe berm fill support or an excavated cell below-grade for more stable downhill to e conditions. The flat at-grade edge of a typical leach pad is shown in Figure 9.

The rare exception to external leach pad gravity drainage is the valley heap leach pad, in which internal drainage on the primary base liner is subjected to potential high internal pond hydraulic heads within the heap fill. The valley heap leach operations constructed in modern times with internal solution drainage to bottom sumps have multiple base liner systems for leak detection between the primary and secondary base liner systems. Copper and zinc heap leach

pads may include multiple interlift liner systems above the base leach pad liner, as required for maximizing multiple lift leach metal recovery at reduced operational costs.

The most preferred pad base liner system in current heap leach practice is the single composite soil and geomembrane liner system with an overlying drain cover fill for gravity solution flow to external collection ditches and ponds (Breitenbach, 1999). Several leach pad sites have used the geosynthetic clay liner (GCL), where the compacted clay liner (CCL) borrow material is not available. The primary purpose of the composite pad liner design is to prevent the loss of pad and pond process solutions from the lined facilities for both economic and environmental reasons. Note that the typical hydraulic conductivity goal for the soil portion of the composite liner of a heap leach pad is 1×10^{-6} cm/s, which is ten times higher than the typical requirement for landfill construction. This is discussed further in the landfill liner construction discussion below.

The drain cover fill provides protection to the exposed geomembrane liner and is generally supplemented with drain pipes at a controlled spacing on the liner surface. Relatively clean crushed ore materials are often used as the drain cover fill as much as practical. The drain cover fill and drain pipes provide both rapid drainage recovery of the pregnant solutions to the process pond and plant facilities, as well as maintaining low hydraulic heads above the base pad liner.

Landfill Geocomposite Liner Construction

Solid waste landfills usually have, at a minimum, a single composite or geocomposite liner and overlying leachate collection drainage layer, as described for the heap leach pad. In addition, many landfills have secondary liners and leachate collection systems, and may include protective cushion layers and the use of geocomposite drainage layers in lieu of granular drainage layers. A double-geocomposite liner system using many geosynthetic elements is shown in Figure 7.

Note that the typical hydraulic conductivity goal for the soil portion of the composite liner of a landfill liner is 1×10^{-7} cm/s, which is ten times lower than the typical requirement for heap leach pad composite liner. Requiring lower permeability clays to be used in liner construction will generally result in lower interface shear strengths for both peak and residual conditions. In addition, clayey soils placed wet of optimum moisture content to achieve lower permeabilities have a higher risk of desiccation cracks developing beneath exposed liner, as shown in Figure 10. The wet of optimum clayey soil and geomembrane interface was one of the critical failure planes at the Kettleman Hills facility (Mitchell et al., 1990).

The bottom slopes of landfills can range from 0.5 percent to well over 10 percent, with a 2 to 4 percent bottom slope perhaps representative of an industry norm. Landfills are typically excavated below grade, or have toe berm fills, necessitating slope-riser pipes or vertical sumps for the removal of leachate, as illustrated in Figure 11. The below-grade excavation, or toe berm fill typically constructed for landfills will generally be a benefit to overall stability, as compared to the typical lack of structural toe support in a heap leach pad. The downside to large toe berm

fills is the potential for hydraulic head build-up, if the internal sump system becomes clogged or inoperable.

GENERAL DIFFERENCES RELATED TO STRENGTH

General

The containment fill materials for leach pads and landfills have several strength differences related to fill types, densities, heights, exterior slopes, hydraulic conditions and construction fill placement. The base composite and geocomposite liner systems for the two types of fill structures have construction similarities and differences related to liner materials placed at the liner interface contact, liner grades and toe support conditions. Each of these lined fill structure similarities and differences, as related to strength and fill slope stability, are summarized below, and in Tables 1 and 2.

Containment Fill Types and Shear Strength

Heap Leach Pads

The fill types for leach pads generally consist of drill-and-blast run-of-mine ore rock with cobble and boulder sized rock fragments intermixed, or crushed granular rock varying from sand to gravel sizes. The more fine-grained ore fraction is agglomerated with water to maintain even distribution of fines and enhance ore permeability for leaching. Gold and silver ore may include agglomeration with lime or cement for the more clayey ore materials for improved percolation in the heap. The rock particles are typically angular and high strength. Agglomerated fine ore strengths vary depending on the fines content and the cement additives. The relative change in strength with respect to rock particle size, distribution, and relative density for fine to coarse grained soils is illustrated in Figure 12 (NAVFAC, 1982).

Solid Waste Landfills

The fill material for MSW landfills is typically very heterogeneous consisting of a mixture of plastic, metal, glass, putrescible waste, demolition debris, commercial waste, and industrial waste. The nature of the waste creates a reinforced mass that typically can be constructed to near-vertical faces at heights up to 10 m. Variations in shear strength with depth, density, saturation or age have not been reported other than due to the effects of effective confining stress. The shear strength envelope most commonly used in US practice is presented in Figure 13 (Kavazanjian et al., 1995), and consists of a bi-linear envelope with a friction angle of zero and cohesion of 24 kPa at effective stresses below 30 kPa, and a friction angle of 33° with zero cohesion at effective stresses greater than 30 kPa. A testimony to the temporary high shear strength of solid waste, especially at low confining pressures, is shown in Figure 14 with a near-vertical tipping face over 10 m high.

Containment Fill Density

Heap Leach Pads

The ore heap density varies from a loose dry fill material during lift placement to a uniformly wetted, loaded, and consolidated dense granular fill over time from multiple lift heap leaching operations. Each granular ore lift is wetted in a fully drained condition and subsequently loaded with successive stacked ore lift layers over a period of several months between lift layers. The spent ore material generally consolidates by about 7 to 10 percent for gold and silver heaps and by about 10 to 15 percent for copper and zinc heaps.

Most of the heap densification occurs within the first 50 to 100 ft (15 to 30 m) of ore heap fill. Ore heap fill dry densities generally vary from 100 to 120 pcf (1.6 to 1.9 tonnes per cubic meter). Typical heap moist unit weight densities range from 110 to 130 pcf (1.8 to 2.1 tonnes per cubic meter) with maximum unit weight densities occurring during leaching operations. A typical consolidation versus ore lift loading laboratory test curve for crushed gold and copper ore heap material is shown on Figure 15.

Solid Waste Landfills

Average values for MSW unit weight cited by landfill operations and used in practice for landfill capacity estimates typically vary from 8.6 to 10.2 kN/m³ (55 to 65 lbs/ft³) (Kavazanjian et al., 1995). The variation of density with depth can have a small influence on the results of static stability, and a significant influence on dynamic stability and seismic response analyses. The line on Figure 16 shows this density-depth relationship developed for one southern California landfill (Puente Hills) based on field measurements of density and laboratory measurements of waste compressibility (Earth Technology, 1988). Based upon the Earth Technology density-depth profile, the initial and average unit weights cited above, and representative compressibility values reported for MSW facilities (Fassett et al., 1994), a "Puente Hills" MSW unit weight profile was developed (Kavazanjian et al., 1995) as shown by the solid line on Figure 16. This is commonly used in stability analyses of MSW landfills in the absence of landfill-specific data. It is useful to note that the data for Figure 16 was developed for a relatively dry landfill. A method has been suggested for adjusting the density for wetter landfills (Richardson and Thiel, 2001). The second author typically uses a value on the order 13 kN/m³ (82 pcf) for his analyses.

Containment Fill Heights

Heap Leach Pads

The heap leach pad maximum fill heights typically range from 100 to 200 feet (30 to 60 meters) with the highest heaps stacks to date exceeding 500 feet (150 meters). The heap fill heights above about 100 feet (30 meters) generally increase in theoretical slope stability analyses above the geomembrane liner system due to the granular nature of the ore heap fill and the planar wedge geometry (Breitenbach, 2004). Other factors include the elastic deformation of the liner interface contact under high load conditions and the change in ore density from controlled

multiple ore lift construction and wetting from leaching. The slope stability improvement with heap height assumes competent and drained foundation conditions below the liner system and no excess hydraulic conditions within the heap fill.

Solid Waste Landfills

MSW landfills vary greatly in size and height. Local landfills for small towns may be as small as 25 to 50 feet high (8 to 15 m). Large mega-landfills can reach heights of 500 feet (150 m). An industry average for modern landfills is perhaps 200 feet high (60 m).

Containment Fill Slopes

Heap Leach Pads

The heap leach pad exterior ore lift fill slopes are constructed at the angle-of-repose with benches included between ore lift stacks for an overall flatter design slope for stability. The heap ore stack slopes are constructed as steep as practical to maximize the tonnage on the pad liner, while maintaining stable exterior slope conditions in operations to closure. A typical angle-of-repose ore heap lift construction with dump truck and dozer placement is shown in Figure 17.

The downhill toe of the leach pad slope is generally the most critical for slope stability with the heap slope unsupported to allow gravity solution drainage flows to lined external ponds. The sidehill and uphill slopes are more stable and sometimes constructed more steep compared to the downhill slope with inward lined solution drainage.

The heap fill slopes for closure depend on site-specific conditions, and generally do not require slope flattening in the dry climate areas with respect to long-term stability on the liner system. Overall outer slopes of 2(H):1(V) are common.

Solid Waste Landfills

Solid waste landfill maximum slopes are typically governed by regulations to be no steeper than 3(H):1(V) for permanent slopes. One reason for this maximum is that the final cover systems for landfills are an important part of the master plan, and veneer stability of the cover system requires flatter slopes for long-term integrity.

Containment Fill Hydraulic Conditions

Heap Leach Pads

The leach pad ore heaps require capture and containment of all flows and storm events on the lined leach pad, collection ditches, and ponds. The 24-hour operational leach solution application flows include significant areas of active leaching on the top ore surface. The total solution flow volume can be greater than the amount of heap infiltration and runoff flow from a 100-year, 24-hour design storm event. The solution flows are pumped in application pipelines to the top of each ore lift surface for low flow area distribution. The flows are collected at the

bottom of the multiple lift ore heap in a drain cover system designed to maintain low hydraulic heads on the pad liner. The ore heap is targeted to be fully drained by controlled leach rates on the top surface and by the underlying base drain system beneath the multiple ore lift fills.

Solid Waste Landfills

In the past, MSW landfills were generally considered to be drained with occasional perched zones of leachate, where it had trouble getting through intermediate cover or old tipping decks. The designs typically were performed so that one foot of head would be the maximum buildup on the bottom liner. With the advent of “bioreactor landfills” and leachate recirculation, there has been some field evidence that leachate collection systems experience some degree of clogging, and leachate head levels could exist above the bottom liner system to a greater extent than originally anticipated. The hydrodynamics within landfills is very complex and heterogeneous.

SLOPE STABILITY COMPARISON

General

Generic slope stability analyses were performed for idealized heap leach and landfill study section configurations chosen by the authors for illustration and comparison purposes. The selected configurations are described in the following table. Example graphs of the geometry, input parameters, and typical results for analyses of a heap leach pad and a landfill are shown in Figures 18 and 19.

Table 3 – Idealized Study Section Assumed Strength Parameters

Strength Parameter	Heap Leach Pad	MSW Landfill
Bottom liner grade	2 %	4 %
Toe berm fill	None	25 ft (8 m) high
Fill slope	200 ft (60 m) high @ 2(H):1(V)	200 ft (60 m) high @ 3(H):1(V)
Liner interface strength	Vary 10 to 24°	Vary 10 to 24°
Fill moist density	120 pcf	75 pcf
Phreatic water surface	2 ft above liner	Up to 100 ft above liner
Fill strength	38° friction and no cohesion	33° friction (see Figure 13)
Foundation subgrade	Assumed high strength	Assumed high strength

Summary of Results

The results for static and seismic stability analyses are presented in Figure 20, as a function of interface shear strength along the bottom liner. The seismic results are presented in terms of yield acceleration. In general, the landfill has slightly higher factors of safety (FS) than the leach pad ore heap, and lower yield acceleration for the assumed strength parameters. This is explainable largely because of the flatter exterior slope.

The theoretical FS may vary compared to construction and operation conditions. As an example, the negative effects of high head levels within a landfill are demonstrated in Figure 21. The FS decreases for a landfill with an inoperable sump system from over 1.6 to less than unity, as the depth of leachate exceeds 50 ft (15 m). In this case, the leach pad would have the higher comparable FS with gravity drainage and no toe berm blockage of flows to an external pond. In addition, the ore heap granular fill strengths appear to increase over time with controlled lift placement and leach wetting, as indicated by most pad slope failures occurring during the initial dry loose lift placement and becoming more stable at higher heap stack heights.

CONCLUSIONS

The tale of two conditions: heap leach pad versus landfill liner strengths is an ongoing story related to the design, construction, and operational aspects of each individual project. There is no clear black and white conclusion to the tale, due to the numerous parameters and variables that can develop throughout the life of the projects to closure. This discussion illustrates some of the common similarities and differences between the two structures and their construction and operational affects on the strength of the base geomembrane liner system. Engineering experience and judgment are required, in addition to a team effort by the owner, engineer, contractor and operator of the facilities to maintain stable slope stability conditions to closure.

Standard liner design and construction practices for heap leach pads and landfills have been discussed in this paper, and generally can be compared relative to liner slope stability concerns, as summarized in Table 4.

Table 4 – Summary Comparison of Typical Liner Stability Concerns

Condition Affecting Slope Stability	Heap Leach Pad Relative Comparison to MSW Landfill	MSW Landfill Relative Comparison to Heap Leach Pad
Exterior Overall Slope	LESS stable due to typical steeper 2H:1V slopes	MORE stable due to typical 3H:1V slopes
Lift Heights (vary for each structure)	LESS stable due to typical higher lifts in exterior slopes	MORE stable due to typical smaller lifts in exterior slopes
Containment Fill Rate of Rise During Initial Operations	LESS stable at startup due to steep angle-of-repose lifts and high change in stress loads on base liner system	MORE stable due to typical benign condition of initial lifts and low change in stress loads on the base liner system
Stability during mid-life of facility	MORE stable after first lift with offset benches and less change in stress on the base liner system	LESS stable due to critical interim high and steep slopes with no interior toe support
Containment Fill Material Strength	MORE stable because of high strength granular dumped rock or agglomerated materials	LESS stable because MSW is not as strong as granular dumped rock and more variable material
Containment Fill Hydraulic Drainage	MORE stable with gravity drainage and typical free-draining condition of granular or agglomerated heap fill	LESS stable with leachate irrigation because of poor drainage and long-term clogging in MSW systems

Condition Affecting Slope Stability	Heap Leach Pad Relative Comparison to MSW Landfill	MSW Landfill Relative Comparison to Heap Leach Pad
Containment Fill Material Settlement	MORE stable with controlled loose lift placement and wetting from controlled leaching under fully drained conditions	LESS stable with variable wetted settlement over time and some differential settlement from waste decomposition
Toe Berm Support or Cell Excavation into Ground	LESS stable due to lack of toe support for external gravity drainage to lined ponds	MORE stable due to typical base support with toe berm fill or excavated cell into subgrade
Interlift Liners Within Containment Fill	LESS stable when interlift liners are used	MORE stable due to minimal use of interlift liners
Base Liners Beneath Containment Fill	MORE stable due to typical single barrier or single composite base liners	LESS stable due to typical use of more liner elements and geocomposite base liners for more potential slip planes
Base Underliner Soil	MORE stable with 1 ft of clayey soil at 1×10^{-6} cm/s minimum	LESS stable with 1 ft of clayey soil at 1×10^{-7} cm/s minimum
Exterior Flow Pipelines	LESS stable with more pumped solution flow volumes for pipe break slope erosion	MORE stable with less leachate pipe recirculation flow volumes for pipe break slope erosion
Interior Flow Pipelines	MORE stable due to applied gravity flow at low application rates per unit surface area and no injection pumping	LESS stable when there is leachate injection due to poor hydraulic conditions and clogging in waste and leachate collection system

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Figure 1. Heap leach operation showing base liner in background, drain placement in canyon bottoms, ore stacking in middle, leaching in bottom right and gravity flow to external ponds.



Figure 2. New MSW landfill cell on the left, tied into existing MSW cell on right and base liner system in background.

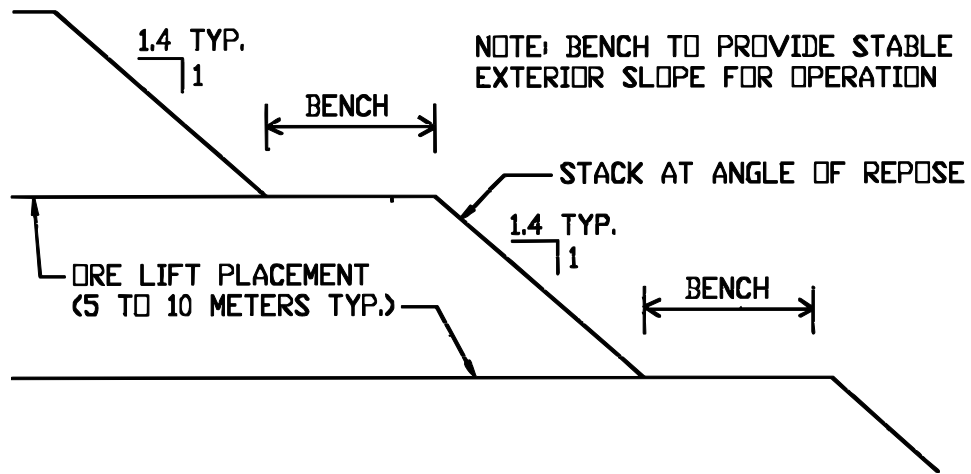


Figure 3. Heap slope section with typical angle-of-repose ore lift slopes and bench setbacks for overall flatter slope.



Figure 4. Drip-emitter recirculation of external barren solution onto ore heap top lift surface for controlled active leaching.



Figure 5. Spray-recirculation of leachate from internal collection sumps onto landfill top lift surface for accelerated bioreactor decomposition of organics.

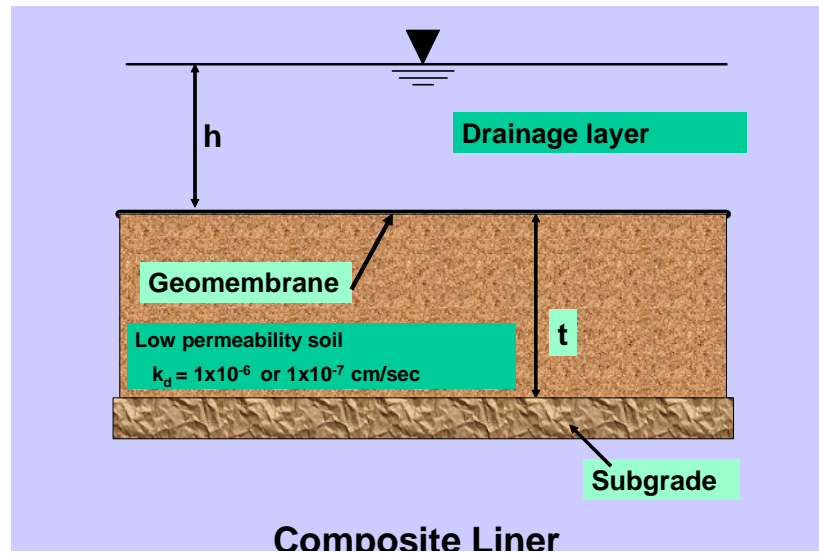


Figure 6. Typical composite soil and geomembrane base liner and overlying drainage layer for leach pad or MSW landfill liner systems.

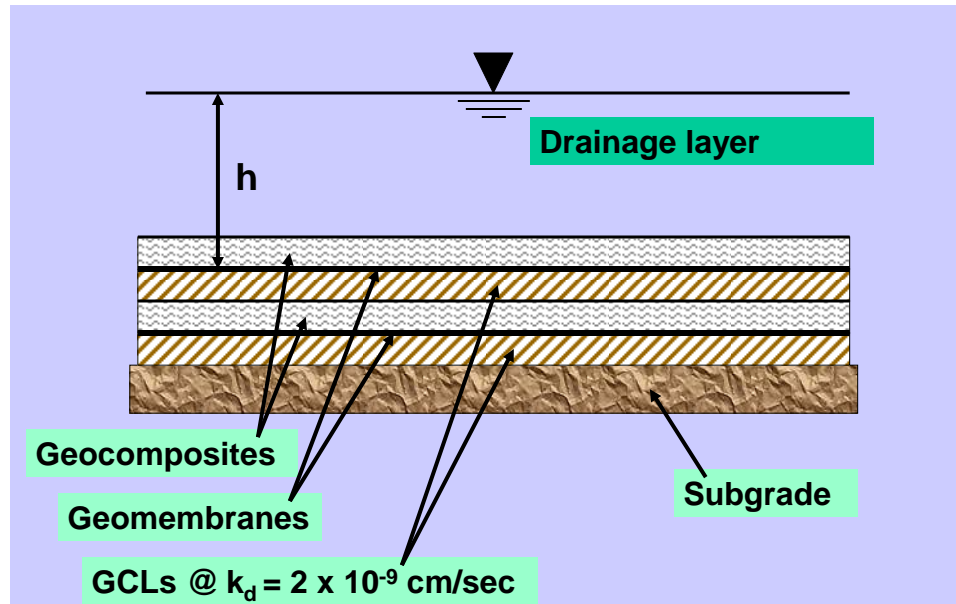


Figure 7. Double geocomposite base liner with many geosynthetic layers where required for multiple layer MSW landfill liner systems.



Figure 8. Typical drain layer placement over heap leach pad base liner. Landfill construction typically would be similar with thinner drain layer thickness and smaller dozer equipment size.



Figure 9. Unsupported toe of leach pad expansion base liner for external solution gravity-flow. Operating heap stack in background with benched slopes and surface spray leaching.



Figure 10. Desiccation cracks in exposed clayey soil liner 1 week after being placed wet of optimum moisture. Shoe toe shown in foreground for reference.



Figure 11. Setting below-grade vertical sump next to toe berm typical of landfill construction on base liner system.

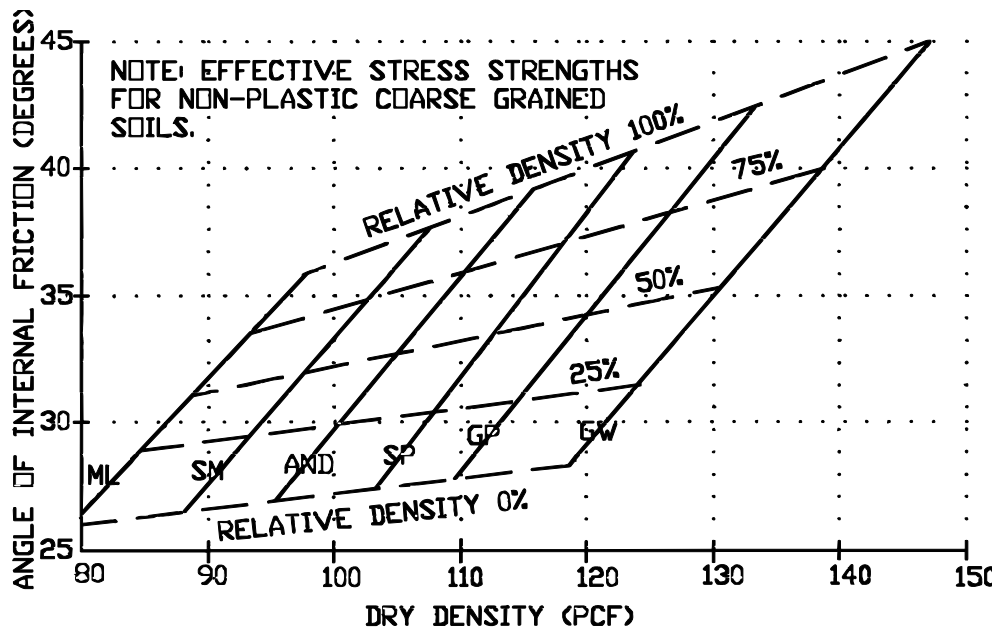


Figure 12. Friction strength versus density for crushed granular rock materials placed in ore heap leach piles (NAVFAC, 1982).

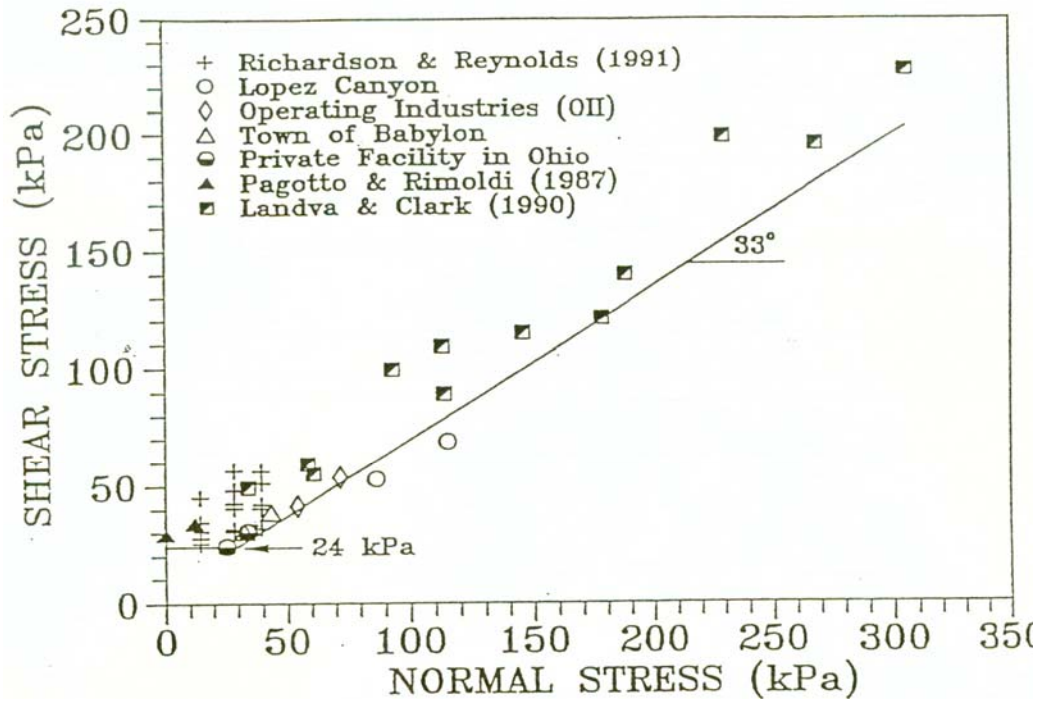


Figure 13. Bi-linear shear strength envelope for MSW (Kavazanjian et al., 1995).



Figure 14. Landfill tip deck with near-vertical 10 m high tipping face with base liner in background.

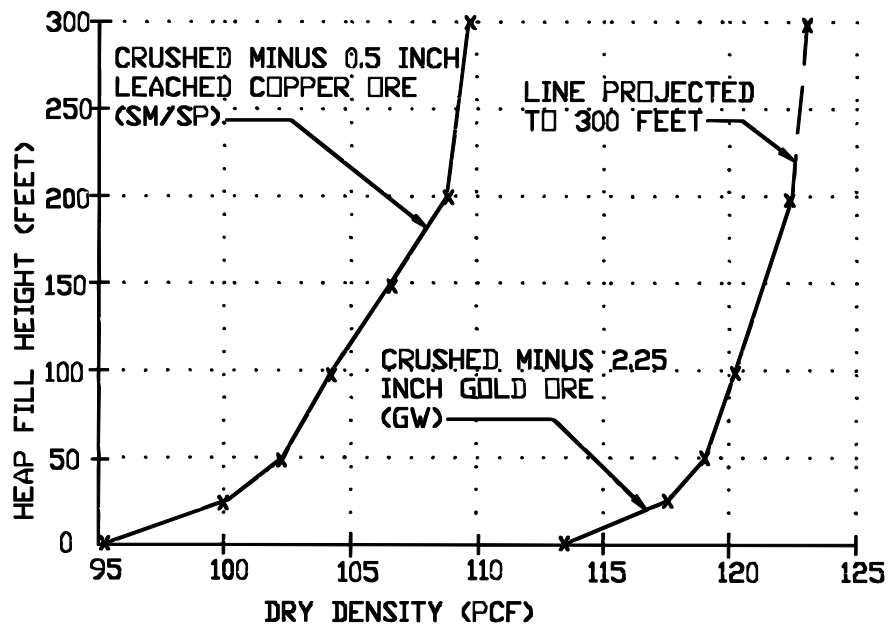


Figure 15. Containment fill height versus dry density for crushed minus 0.5 to 2.25 inch rock materials in ore heaps (Breitenbach, 2004).

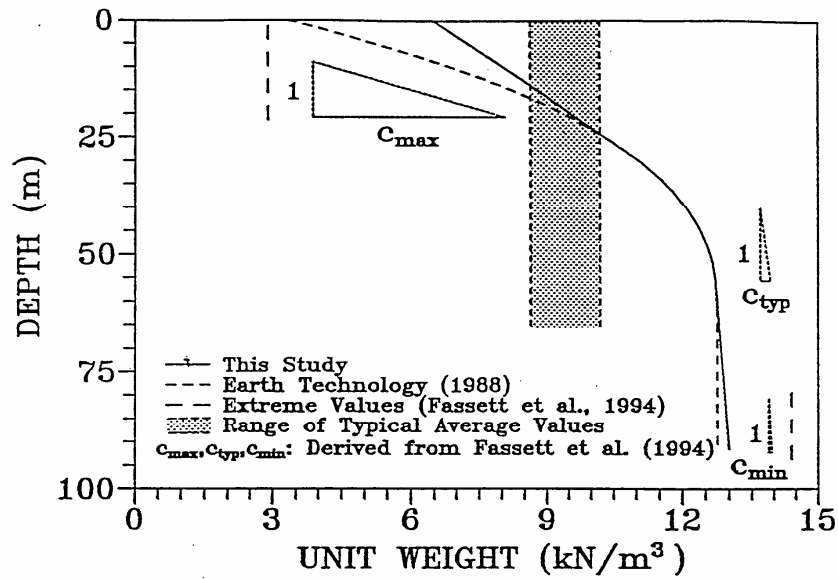


Figure 16. Containment fill depth versus unit weight profile for MSW (Kavazanjian et al., 1995).



Figure 17. Angle-of-repose truck and dozer ore lift placement over lined leach pad. Rock boulders at toe of slope overlying base liner and protective drain fill cover layer.

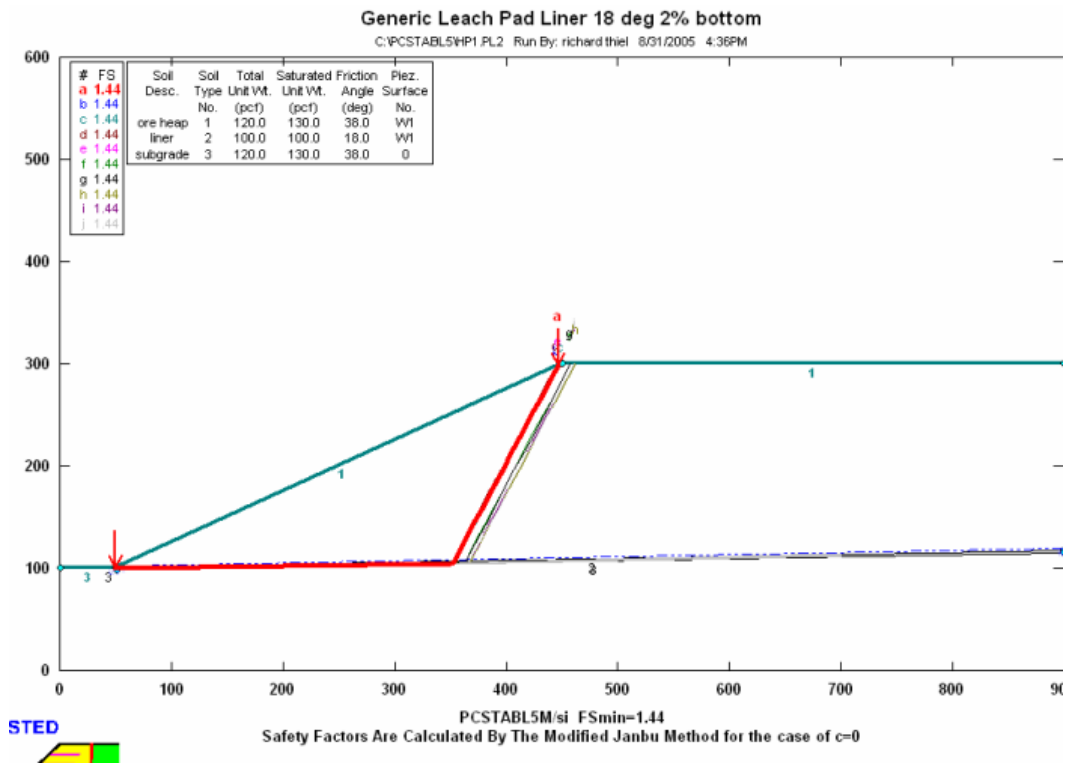


Figure 18. Example analysis of typical ore heap configuration with 2H:1V overall benched slope and no toe berm support for base liner system.

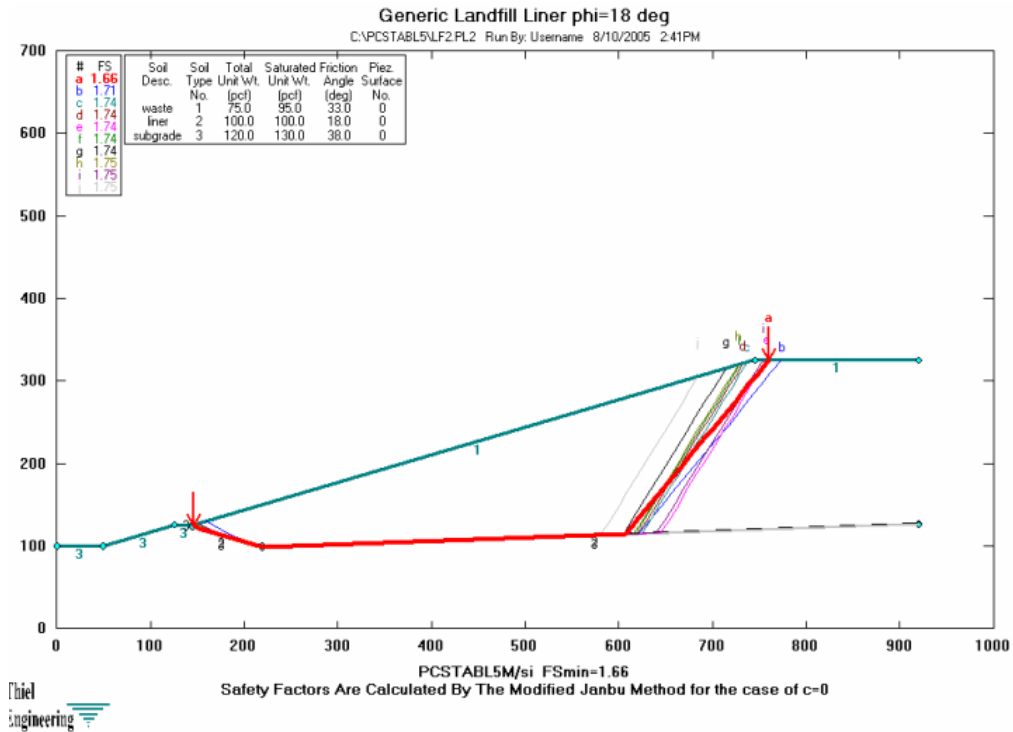


Figure 19. Example analysis of typical landfill configuration with 3H:1V overall slope and toe support for base liner system.

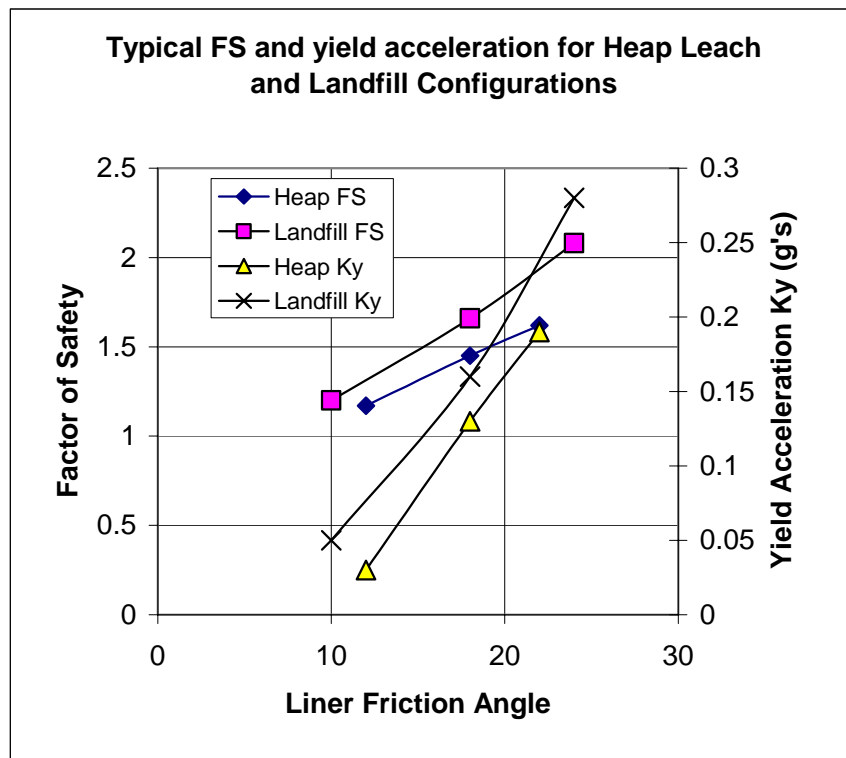


Figure 20. Summary of results for factor of safety and yield acceleration for heap leach pads and landfills with different base liner effective stress shear strengths.

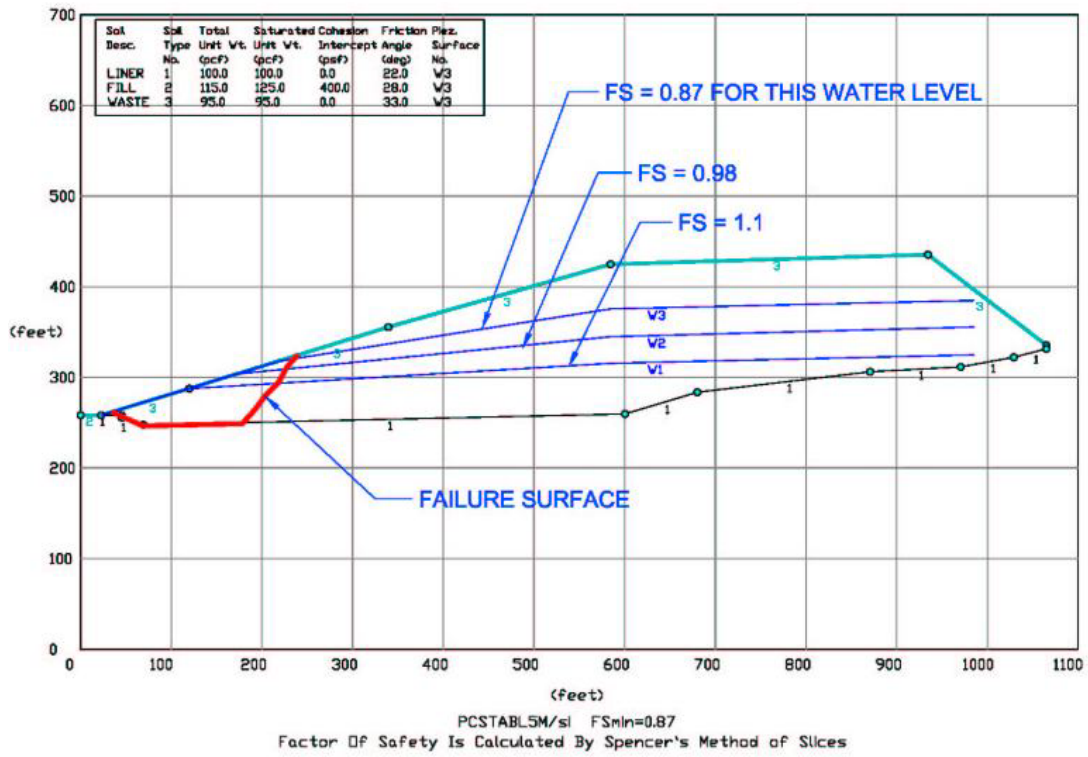


Figure 21. Analysis showing effects on factors of safety for elevated phreatic surfaces in a landfill (Thiel and Christie, 2005).