STABILITY OF WASTE CONTAINMENT FACILITIES

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Paper Submitted to:
Municipal and Industrial Solid Waste Disposal Technology
WasteTech '99
February 1-3, 1999
New Orleans, Louisiana

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January 5, 1999

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ABSTRACT:

A number of recent slope failures demonstrate the challenges in current design, construction, and operation of waste containment facilities. These failures include landfill liner and cover systems and involve both natural and geosynthetic materials. These case histories have been reviewed and are used herein to illustrate the importance of slope stability, solid waste placement rates and quantities, fluid and gas pressures, leachate recirculation, lateral and vertical expansions, and interim or temporary slopes on the stability of landfills. An empirical slope stability chart has been developed and presented herein to evaluate the relative stability of landfill slopes. In general, the empirical relationship indicates that as the slope height increases, the slope angle should decrease to ensure stability. In addition, field reconnaissance techniques for evaluating slope instability are presented.

I. INTRODUCTION

A number of recent slope failures clearly indicate the importance of slope stability on the behavior and performance of waste containment facilities. These failures can be separated into the following two categories based on the material(s) involved in the failure: (i) natural material(s), i.e., soils, related and (ii) geosynthetics related. These failures have occurred under a number of conditions including: (i) during liner construction, (ii) during filling, and (iii) after filling or closure. Tables 1 and 2 present a summary of some of the recent failures involving natural material(s) and geosynthetic(s), respectively.

It must be noted that the majority of landfills are constructed and operated safely. In fact, state-of-practice testing, design, and analysis procedures are readily available to successfully construct and operate waste containment facilities. However, the case histories cited in Tables 1 and 2 illustrate the need for identifying and evaluating the potential failure modes during: (i) liner construction, (ii) lateral and vertical expansion, (iii) relocation of old municipal solid waste especially when consisting primarily of soil (Stark et al. 1998), (iv) rapid waste placement or regrading, (v) typical landfilling, and (vi) final closure. After identifying the potential failure modes, stability evaluations should as a minimum include the selection of the appropriate slope geometry, cross section(s), shear strength parameters (and thus laboratory testing requirements), fluid or gas pressure conditions, slope stability analysis, and actual construction materials and/or geosynthetics.

Careful construction and operating procedures based on the analysis results should be undertaken to ensure that:

- landfill construction proceeds according to design
- toe excavations are limited in extent and time

Table 1. Recent landfill slope failures involving natural material(s) underlying the waste.

CASE HISTORY	DATE	SLOPE INCLINATION	SLOPE HEIGHT (m)	FAILURE MODE	VOLUME OF SLIDE MASS (m^3)	DESCRIPTION OF NATURAL MATERIAL AND CIRUMSTANCES CONTRIBUTING TO FAILURE
(Natural) N-1	1984	1V:4H	44	Rotational	110,000	Soft clay underlying waste – importance of rainfall and slope loading
N-2	1988	1V:3H	20	Rotational	500,000	Soft clay underlying waste – importance of toe excavation, slope loading, and rainfall
N-3	1996	1V:1.8-2.6H	98	Translational	1,100,000	Native residual/colluvial soil underlying waste – importance of toe excavation and slope loading
N-4	1997	1V:3.5H	6	Translational	150,000	Native colluvial soil underlying the waste – importance of unbuttressed toe and rainfall
N-5	1997	1V:1.5-2H	32	Rotational/ Translational	250,000	Native medium to stiff clay underlying the waste – importance of rate of loading

Table 2. Recent landfill slope failures involving geosynthetics.

CASE HISTORY	DATE	SLOPE INCLINATION	SLOPE HEIGHT (m)	FAILURE MODE	VOLUME OF SLIDE MASS (m^3)	DESCRIPTION OF PRIMARY SLIDING SURFACE
(Geosynthetics) G-1	1988	1V:3.4H	31	Translational	490,000	Compacted clay liner/smooth geomembrane interface
G-2	1994	1V:2H	12-20	Translational	60,000	Compacted clay liner/smooth geomembrane interface on sideslope and compacted clay liner/geotextile interface on base
G-3	1996	1V:2.5H	35	Translational	229,200	Compacted clay liner/unreinforced GCL interface
*G-4	1996	1V:3.5H	1.5	Translational	5,000	Sand drainage layer/smooth geomembrane interface
G-5	1996	1V:3H	1.5	Translational	6,000	Compacted clay liner/smooth geomembrane interface
*G-6	1996	1V:4H	0.9	Translational	12,000	Smooth geomembrane/GCL interface
G-7	1996	1V:2H	0.6	Translational	2,000	Gravel drainage layer/textured geomembrane interface

Note: * designates a landfill cover system

Table 2. Recent landfill slope failures involving geosynthetics (continued).

G-8	1997	1V:2H	0.3	Translational	1,000	Interface between two hydrated GCLs
G-9	1997	1V:3H	1.5	Translational	6,000	Compacted clay liner/smooth geomembrane interface
G-10	1997	1V:3.5-4H	67	Translational/ Flow	1,200,000	Sliding above smooth geomembrane due to high fluid pressures induced from leachate recirculation
G-11	1997	1V:2-3H	4	Translational/ Flow	7,000	Sliding above smooth geomembrane due to high fluid pressures induced from leachate recirculation and surface runoff
G-12	1997	1V:2.5H	61	Translational/ Flow	300,000	Sliding above smooth geomembrane due to high fluid pressures induced from leachate recirculation and surface runoff
G-13	1998	1V:1.5H	10	Translational/ Flow	55,000	Mined agglomerated gravel/rockfill – importance of lixiviation process

Note: * designates a landfill cover system

- lateral expansions proceed according to schedule to minimize the time a slope toe is unbuttressed

- actual filling schedules or rates correspond to the design assumptions

- slope overfilling and/or oversteepening does not occur

- contingency plans are available in the event of changed conditions during construction and filling, such as excessive rain, inadequate surface runoff control, unexpected foundation conditions, aggressive leachate recirculation, reduced airspace, construction delays, etc.

- waste diversion plans are available and can be implemented so slopes are not overbuilt and/or oversteepened due to construction delays or absence of permitted airspace

II. FAILURE MODES

There are two primary failure modes for landfill slopes: translational and rotational (see Figure 1). In a translational failure the slide mass usually progresses out or down from the original slope along a planar or gently undulating surface. A translational failure will have little of the rotational movement or backward tilting characteristic of a rotational failure. A translational slide can be larger and more significant than a rotational slide if the failure surface is sufficiently inclined, the shear resistance along this surface remains lower than the driving force, and there is an open space for the waste to move. Conversely, a rotational movement tends to restore equilibrium in the unstable mass because the driving moment during movement decreases as the toe of the slope moves upward.

The movement of a translational slide is commonly controlled by a weak surface, such as a slickensided surface in cohesive soils, the contact between firm bedrock and overlying detritus, such as colluvium, variations in shear strength between layers of bedded deposits, faults, joints, bedding planes, and of course geosynthetic interfaces. In most translational slides, the slide mass is greatly deformed or breaks into many more or less independent units. As deformation and disintegration continue, the broken or disrupted slide mass may change/mobilize into a flow slide.

It can be seen from Tables 1 and 2 that the majority of the failures involve a translational mode of failure. This is especially evident for the geosynthetic cases because a weak interface can be present in a liner or cover system with geosynthetic interfaces. It can also be seen that some of these translational failures involved a large slide mass. As mentioned previously, this was probably caused by the failure surface being inclined, e.g., a sloping liner system for leachate collection purposes or the natural topography, the shear resistance along the failure surface remaining less than the driving force, and most importantly an open space being present at the toe of the slope, which allowed the waste to move. This open space was usually created by a lateral expansion.

In these translational failures, it is anticipated that the weak failure surface was not recognized during design, construction, and operation resulting in the slope failure. This hypothesis is suggested because the failure surface is usually well defined by a weak natural material(s) or a geosynthetic interface(s). Remedial measures for slope instability usually include: (1) termination of waste placement in the potential slide area, (2) unloading and/or flattening the slope, (3) buttressing the toe of the slope, and (4) increasing the shear strength along the failure surface. Since the failure surface is well defined in a translational failure, the area that needs to be unloaded, the location of the buttress, and the shear strength that needs to be increased are well defined.

In contrast, a rotational failure typically occurs in a homogeneous material and usually involves a progressive failure mechanism. An example of this mode of failure is a waste containment facility constructed over a soft soil/clay (see Figure 1). The failure develops in the soft soil/clay and the overlying stronger waste is rotated until the driving force is less than the remaining shear resistance of the soft soil/clay. The movement is more or less rotational about an axis parallel to the slope. In the scarp area, the movement may be almost downward and have little apparent rotation; however, the top surface of each unit commonly tilts backward toward the slope.

III. CASE HISTORIES

All of the case histories listed in Tables 1 and 2 involve failure of or underneath a landfill liner system except for two of the cases in Table 2. These two cases (G-4 and G-6) involve failure along a geosynthetic interface in a composite cover system. Several of the cases (G-5, G-7, G-8, and G-9) involve failure during placement of the soil drainage layer over the geomembrane during liner construction or a similar situation. As a result, the slope height and volume of slide mass for these cases are small.

The data in Tables 1 and 2 that do not pertain to cover system or construction failures (N-1 through N-5, G-1 through G-3, and G-10 through G-13) can be used to develop a slope stability chart for municipal solid waste landfills. This slope stability chart (Figure 2) can be used to evaluate the relative stability of landfill slopes. The concept of a slope stability chart was developed by Bjerrum, and presented by Shannon and Wilson (1964), in response to the slope failures induced in Anchorage, Alaska during the 1964 Alaskan earthquake.

Figure 2 presents the slope stability chart, which can be used a convenient guide for the rapid evaluation of potentially stable and unstable landfill slopes. This chart should not preclude site-specific slope stability analyses and shear strength testing for any landfill slope or condition. In particular, this relationship does not explicitly account for inclination of the failure surface, progressive failure, toe excavation, fluid pressures, leachate recirculation, or the rate and magnitude of waste placement.

Figure 2 presents the slope height and slope angle for the landfill slope failures that do not involve a composite cover system or a failure during liner construction. The case histories involving natural materials do not appear to produce a consistent trend. This is probably due to the limited number of case histories, the wide variety of soil or natural materials involved in these failures, and the variation in the rate and magnitude of loading. For example, some of the cases involved saturated soft clay (N-1 and N-2) while another case involved saturated medium to stiff clay (N-5). The rate and magnitude of loading are extremely important with cohesive soils because excess pore-water pressures induced by waste placement cannot dissipate rapidly. This can lead to an undrained failure condition. A staged loading analysis, e.g., Ladd (1991), is recommended for waste placement on saturated cohesive soils.

The geosynthetic case histories in Figure 2 appear to present a consistent trend probably due to the smaller variability in the shear strength characteristics of geosynthetic interfaces. In general, it can be seen that a trend line or relationship was plotted at the lower bound of the geosynthetic case histories. This trend line brackets all of the cases except for G-11, which involves a shallow failure of a soil berm over a geomembrane. The soil berm displaced into the new cell that was being constructed adjacent to the berm (Stark et al. 1999). Therefore, this relationship can be assumed to separate cases of failure (above the trend line) from those of non-failure (below the trend line) and used to evaluate the relative stability of landfill slopes. In general, the trend indicates that if the slope height increases, the slope angle should decrease. Conversely, if the slope angle increases, the slope height should decrease to ensure stability. For example, if the slope height and slope angle for a geosynthetic liner system plots above the trend line in Figure 2, there is precedence for such a slope geometry to fail. If the slope height and angle for a geosynthetic liner system plots below the trend line, there is precedence for such a slope geometry to be stable. Another application for this slope stability chart is for regulatory personnel to quickly assess whether a slope geometry might be potentially unstable.

Figure 3 presents the data from Figure 2 in a slightly different format. Instead of slope angle, the horizontal component of the slope inclination is used. For example, a 1V:2H slope corresponds to the number 2 on the vertical axis. In general, it can be seen that a trend line is plotted above the majority of the geosynthetic case histories. Therefore, this relationship separates cases of failure (below the trend line) from those of non-failure (above the trend line). It can be seen that the trend line suggests that an allowable slope height for a 1V:2H slope underlain by a geosynthetic liner system is approximately 14 m. It is important to note again that the trend line is a lower bound for the geosynthetic lined slopes that failed. This trend line does not preclude the possibility that a slope geometry, which plots above the relationship can be stable. Such slopes could be stable with careful management and filling of the slope.

Figure 3 can also be used to suggest that a slope stability analysis should be conducted for slopes steeper than 1V:4H. This is suggested because most, if not all, of the failures involve slopes steeper than 1V:4H. Suggestions for the information that should be included in such a slope stability analysis are presented in Section IV.

IV. RECOMMENDED SLOPE STABILITY INFORMATION

The specific contents of a slope stability analysis are sensitive to particular conditions present at an individual site and often need to be assessed on a case by case basis. However, in general, a slope stability analysis for a sanitary landfill should include the following (after Evans, 1997):

- The rationale, cross-sections, and plan views for critical slope conditions* that may occur during the excavation and construction of the landfill**
- The rationale, cross-sections, and plan views for critical slope conditions* that may occur during the operation and filling of the landfill**
- The rationale, cross-sections, and plan views for critical slope conditions* that may occur during the lateral expansion of the landfill**
- The rationale, cross-sections, and plan views for critical slope conditions* that may occur during closure and post-closure of the landfill
- The rationale for selection of soil and geosynthetic interface strength characteristics, including detailed information from a site specific subsurface exploration, and detailed information from a project specific geosynthetic shear strength testing program
- A discussion of the methodology used for the determination of the factors of safety including a summary of the input parameters, e.g., shear strength, unit weight, and fluid or gas pressure
- The physical calculations and/or computer output for the critical conditions of

the excavation, interim, and final slopes

* Determining critical slope conditions includes investigating both static and seismic cases for both deep-seated and shallow failure surfaces and for rotational and translational modes of failure.

** Operational and construction practices can have a profound impact upon the integrity of the engineered components of waste containment facilities and should not be overlooked in the design process.

V. LIMIT EQUILIBRIUM SLOPE STABILITY METHODS

Two-dimensional limit equilibrium stability methods are applicable to practical problems because they can accommodate circular and non-circular slip surfaces, variable soil properties, and fluid or gas pressures in the slope or cross-section. Duncan (1992, 1996) showed that limit equilibrium stability methods that satisfy all conditions of equilibrium, i.e., vertical force equilibrium, horizontal force equilibrium, individual slice moment equilibrium, and overall moment equilibrium, yield factors of safety that are within 5 percent of the correct answer. This small error is substantially less than that which can be caused by an input error. Therefore, the majority of the time and effort should be spent on defining the slope geometry, realistic failure modes/surfaces, fluid or gas pressures, unit weights, and shear strength information after selecting a stability method that satisfies all conditions of equilibrium, e.g., Janbu (1957), Morgenstern and Price (1965), and Spencer (1967).

When selecting a software package one of the most important factors is the stability method(s) used by the software package. Methods that satisfy all conditions of equilibrium should yield accurate results and thus software that utilizes these methods should be selected. Additional questions to ask when selecting a slope stability software package include:

- What slip surface geometries can be analyzed (e.g., rotational and/or translational)?
- What are the shear strength options (e.g., non-linear failure envelopes)?
- What are the options for incorporating fluid and/or gas pressures?
- What are the input and output techniques?

Verification of the factor of safety computed by a slope stability software package can be accomplished using one of the following techniques:

- Use of more than one slope stability program and ensure reasonable agreement between the calculated values of F.S. for the same stability analysis method
- Use of hand calculations
- Use of slope stability charts

At present, most slope stability analyses are performed using a two-dimensional (2-D) limit equilibrium method. These methods calculate the factor of safety against failure for a slope assuming a plane-strain condition. Therefore, it is implicitly assumed that the slip surface is infinitely wide, and thus three-dimensional (3-D) effects are negligible because of the infinite width of the slide mass. Clearly, slopes are not infinitely wide and 3-D effects influence the stability of most, if not all, slopes. In general, a 2-D analysis is appropriate for slope design because it yields a conservative estimate of the factor of safety (Duncan 1992).

A 3-D analysis is beneficial in designing slopes with a complicated topography, shear strength, and/or fluid or gas pressure condition. For these cases, determining the direction of movement that leads to the minimum factor of safety and estimating the value of this factor requires combining the effects of slope geometry and shear strength. This can be accomplished using a 3-D analysis (Stark and Eid 1998). An excellent example of this is expansion of a waste containment facility that results in waste resting on two different types of liner system, e.g., a compacted clay liner and a geosynthetic composite liner system (Stark and Eid 1998). These two liner systems have significantly different shear resistances and it is difficult to quantify the contribution of each liner system to the overall stability using a 2-D analysis. A 3-D analysis is recommended for back-analysis of slope failures so that the back-calculated or mobilized shear strength reflects the 3-D end effects. A 2-D back-analysis will overestimate the mobilized shear strength. The back-calculated shear strength can be used in calculations for remedial measures for failed slopes or initial slope design at sites with similar conditions (Stark and Eid 1998).

VI. METHODS OF FIELD EVALUATION OF SLOPE INSTABILITY

Cracks on the ground surface can be crucial to understanding the details of wasteslide/landslide processes and causes. Therefore, particular attention should be paid to these features and detailed notes and sketches should be made. In addition, "tell-tales," or other types of displacement measuring devices, should be installed across the crack(s). Monitoring of these devices will provide an indication of the rate and direction of the movement. A tell-tale could consist of two pieces of wood placed across the crack and anchored to opposite sides of the crack. Initially the pieces of wood would be in contact with each other and thus slope movement would cause any separation between the wood pieces. After installation the wood pieces should be marked to show the current width of the crack. Of course commercially available tell-tales can be used instead of two pieces of wood. It should be noted that surface cracks are not necessarily normal to the direction of ground movement. For example, cracks near the head of a slide are usually normal to the direction of horizontal movement, but the cracks along its flank are usually parallel to it.

A major problem in waste containment facilities is distinguishing between settlement induced cracks and slope instability related cracks. In general, the re-appearance of cracking in the same location in a short period of time is more likely an indication of slope instability than settlement. In general, settlement cracks will not re-appear in a short period of time in the same location because the biological and mechanical processes that cause the settlement require time. If it is determined that the cracking is due to slope instability, one or more of the remedial measures discussed previously should be considered to try to arrest the movement. The rememdial measure(s) selected, if any, will depend on how rapidly the slope is moving. In any case, waste placement in the potential slide area should cease immediately. The rate of displacement should be determined with "tell-tales," or other suitable device, prior to commencing remedial measures.

Small en echelon cracks commonly develop in the surface soil before other signs of rupture take place; thus they are particularly important in the recognition of potential or incipient slides. They result from a force couple in which the angle between the direction of motion and that of the cracks is a function of the location within the landslide area. Thus in many cases a map of the en echelon cracks will delineate the slide mass accurately, even though no other visible movement has taken place (Rib and Liang 1978).

In addition to indicating actual movement, cracks in surface soils are useful in determining the type of slide that is occurring. For example, in a rotational failure, the walls of cracks are slightly curved in the vertical plane and concave towards the direction of movement; if the rotating block has an appreciable vertical offset, the curved cracks wedge shut at depth. In translational slides, the cracks are nearly equal in width from top to bottom and do not wedge out at depth because failure in a translational slide begins with tension at the base of the block and progresses upward towards the surface. The inclination of cracks is commonly vertical in translational slides, regardless of the dip of the failure surface. If most of the surface cracks are essentially parallel to the slope face, a translational slide is probably initiating. If the outline of the crack pattern is horseshoe-shaped in plan, a rotational slide is likely occurring (Varnes 1978).

The timing of breakage of leachate/liquid and gas lines, drainage ditches, electrical cables, and similar utilities can suggest the sequence of deformation before field observations or measurements. Measuring the tilt of structures or trees assumed to be vertical before movement also can yield an estimate of the amount of displacement on certain parts of the slope. Of course, tilted trees also can be used to ascertain that the slope has moved previously.

Field reconnaissance of slopes for signs of instability should include:

- Inspect the top of the slope for tension cracks or vertical offsets
- Inspect the bottom (toe) of the slope for uplift, heave, bulging, or lateral displacement
- Determine if there is seepage exiting the slope or toe

- Determine if there is any erosion or excavation at the toe

- Determine if the slope is too steep, e.g., steeper than 1V:3H, and/or overbuilt. This can be accomplished using surveying techniques or comparing waste grades from semi-annual or annual reports submitted by the owner/operator. This comparison can also be used to determine how much, if any, overbuild has occurred

- If movement is detected, install "tell-tales" and, if possible, a slope inclinometer to determine the slide surface location and velocity of the slide mass movement. This may not be feasible or advised through a composite liner system

VII. CONCLUSIONS

Even though a number of slope failures have occurred in waste containment facilities, the majority of landfills are constructed and operated safely. Some of these slope failures have been used herein to develop an empirical slope stability chart for waste containment facilities. This slope stability chart can be used to evaluate the <u>relative</u> stability of landfill slopes. This chart <u>should not</u> preclude site specific slope stability analyses and shear strength testing. In general, the empirical relationship indicates that if the slope height increases, the slope angle should decrease. Conversely, if the slope angle increases, the slope height should decrease to ensure stability.

Recommendations are presented on the information and situations that should be included and analyzed, respectively, in a comprehensive slope stability analysis for a waste containment facility. The information should include the shear resistance of the natural soil(s) and geosynthetic interfaces that underlie the waste containment facility and the situations should include construction, interim, and final slopes. A number of the failures utilized herein-involved interim slopes with and without toe excavations. As a result, the stability of interim slopes and toe excavations should be considered even though it may not be required by regulations.

Finally, methods for field evaluation of slope instability based on field reconnaissance are presented. The presence of cracks at the top of a slope can be crucial to understanding the details of an impending slope failure. These cracks should be instrumented immediately to determine the rate and direction of cracking. This information will help determine whether the cracks are settlement or slope instability induced. In general, the re-appearance of cracking in the same location in a short period of time is more likely an indication of slope instability than settlement. Settlement cracks usually will not re-appear in the same location in a short period of time because the biological and mechanical processes that cause the settlement require time.

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EDUCATION

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News Correspondent Award, American Society of Civil Engineers (ASCE), 1995

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