Major Parameters that Affect Outcome of Landfill Slope Stability Modeling

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EXECUTIVE SUMMARY

Slope stability evaluation in a landfill environment, in which significant volumes of leachate are generated or other liquids are introduced into the waste mass, is influenced by many factors. These factors include the bottom liner system's weakest interface shear strength, landfill leachate level management, waste shear strength changes from decomposition, landfill gas management practices, in-place waste density, landfill operations and filling sequences, and final landfill slope configurations. Analytical and stability modeling experience are necessary to predict the landfill slope performance under typical landfill operation and final slope configuration by calculating its factor of safety against instability.

Modern sanitary landfills should be engineered, constructed, monitored and operated purposefully to be stable under anticipated loading conditions. The bottom liner system's interface shear strength evaluation is very important to identify the weakest interface with the lowest shear strength resulting in the lowest factor of safety against slope movement. Landfill operations are critical to maintain stability by minimizing leachate head build-up above the bottom liner system.

This paper focuses on the effects of two major parameters on the factor of safety calculated against landfill slope instability, namely the bottom liner interface shear strengths and the liquid level above the liner system. A case study is presented to show that it is possible to improve the factor of safety against slope failure by improving the interface friction angle of the weakest interface using certain length of a textured geomembrane on the cell floor. In addition, a presence of leachate level above the liner system will have a significant impact on the calculated factor of safety. Other factors mentioned above are not presented in this paper; however, their importance and influence to the factor of safety against slope failure should not be ignored and should be routinely evaluated.

Key Words: Factor of safety, landfill slope, slope stability, liner interface shear strength, leachate level, leachate head on liner, textured geomembrane

INTRODUCTION

The interface shear strength of the bottom liner system and its leachate level above the liner system are two most critical parameters that have significant influence on the calculated factor of safety against slope failure. The interface shear strength of selected geosynthetic or soil materials can be tested and measured during the design and construction phases. The leachate level can be predicted during design phase using HELP model and it can also be measured during landfill operation phase. For the interface shear strength between the geosynthetic/geosynthetic materials, there are abundant published typical values available. However, selection or use of these published data, such as those values presented in Table 1, needs to match a particular site specific design criteria and loading conditions. It is always prudent to perform site-specific testing in determining the lowest liner interface shear strength during construction, if not during the final design phase.

A case study was presented to illustrate the sensitivity and its impact on the calculated factor of safety by changing the leachate level and the liner interface shear strength of the weakest interface. As illustrated from the results of this sensitivity study, it is recommended that site-specific testing of the liner interfaces needs to be performed during the design phase before specifying its value for material selection during construction. It is important to monitor and minimize the leachate level above the liner system during landfill operation such that it results with an acceptable factor of safety against slope movement during landfill operation and landfill final slope phases.

When performing a slope stability analysis in landfill environment, it is important to identity key parameters that have significant influence on the calculated factor of safety against slope failure. These key parameters used in a slope stability analysis should be made site-specific to the landfill evaluated for its functional stability and are listed as follow:

- Foundation Conditions: The location and extent of each type of soil materials beneath the ground surface (or below the bottom of the landfill) that could affect the stability analysis needs to be identified. This includes presence of groundwater table below the bottom of the landfill subbase.
- Soil and geosynthetic Interfaces: The presence of soil/geosynthetic and geosynthetic/ geosynthetic interfaces must be considered, as these interfaces are continuous interfaces that usually are weaker than the soil layer(s) below the landfill. It is common to perform circular and non-circular stability analyses through the waste mass itself and along the most critical interface, respectively. Non-circular or block-type or wedge failure sufaces are usually corresponded to the lowest factor of safety calculated.
- Selection of Critical Cross Sections: This involves identifying few critical sections that are perpendicular to landfill slopes and that potentially yield the lowest calculated factor of safety.
- Waste unit weight and shear Strength: The selected values of waste unit weight and its shear strength will have impact on the calculated factor of safety because stabilizing forces are primarily a function of material shear strength against its driving forces.
- Phreatic surfaces: The presence of liquid level within the waste body will decrease the effective normal stress and decrease the shear resistance of the waste at the weakest interface. Therefore, consideration of the liquid level within the waste is critical.
- Operating Conditions: Develop project operating plans to control liquids infiltrating into the waste mass.
- Monitoring: Monitor landfill performance to confirm that the observed field conditions match those that were assumed in the analysis.

MAJOR PARAMETERS CONSIDERED

Two major parameters were selected to show the effect of their sensitivity to the value of the calculated factor of safety against slope movement. These are the bottom liner system interface shear strengths and the liquid level above the bottom liner system.

Liner Interface Shear Strengths

The design of a bottom liner system of a sanitary landfill may have as much as five to eight interfaces, depending on if the liner system is a single or double composite liner system. Typical geosynthetic/geosynthetic or soil/geosynthetic liner interfaces are well-documented and published for typical geosynthetic materials of various thicknesses and products. Table 1 shows these typical values that can be used for a slope stability analysis during preliminary design phase. These values were published by Geosynthetic Research Institute (GRI) paper, GRI #30. It should be noted that it is common to use the peak shear strength value for the interface at landfill cell floor and the residual shear strength value for the interfacae on landfill sideslope liner system. The internal soil shear strength of the clay liner or foundation layer(s) is usually not lower than the value of the weakest interface. A parametric analysis will be conducted and presented in this paper to illustrate the sensitivity of the interface shear strength value on the calculated factor of safety, assuming zero liquid level above the liner scenario.

Table 1. Published Interface Shear Strength Parameters[1]

Interface	Peak Shear Strength		Residual Shear Strength	
	Friction Angle (deg)	Adhesion (KPa)	Friction Angle (deg)	Adhesion (KPa)
HDPE-S/Cohesive Soil, Saturated	11	7	11	0
HDPE-T/Cohesive Soil, Saturated	18	10	16	0
HDPE-S/Granular Soil	21	0	17	0
HDPE-T/Granular Soil	34	0	31	0
HDPE-S/Geocomposite Drainage Net	15	0	12	0
HDPE-T/Geocomposite Drainage Net	26	0	15	0
HDPE-T/Geosynthetic Clay Liner (GCL)	23	0	13	0
Geocomposite Drainage Net/Granular Soil	27	14	21	8

1 Taken from GRI Paper #30; HDPE – High Density Polyethylene geomembrane; S – Smooth; T - Textured

Leachate Levels

Improper landfill operation surface grading and lack of daily soil cover will increase the infiltration to the waste mass below, especially during seasonal heavy rainfall event(s) where there is no cap system to control excessive infiltration into the waste mass. As a result, the leachate level at the bottom of the landfill may raise to a level which triggers a slope instability condition. In addition, accepting wet or saturated waste sludge and placing it on the exterior of the final slope configuration will result in a perched liquid level that will also lower the factor of safety against slope instability. At an increased amount of moisture content within the waste, waste shear strength may be reduced and pore water pressure may build up to a point where slope stability of the landfill may become a serious concern. Other similar situations such as where leachate is recirculated or bioreactor landfill procedure is implemented, will result in higher moisture content within the waste mass to reach above 40 percent, causing accelerated waste decomposition which results in lower shear strength. In this paper, a parametric analysis will be conducted and presented to evaluate the effect of leachate level above the bottom liner system on the factor of safety, assuming the waste shear strength is unchanged.

SLOPE STABILITY EVALUATION

The landfill designer must demonstrate that the landfill operation and final slope configuration is stable under the proposed and site-specific operating conditions by performing a comprehensive slope stability analysis. The stability analysis typically performed for a waste slope considers either a deep-seated potential failure mode within the waste mass or along discrete bottom liner system interfaces. Limiting equilibrium methods that are common in geotechnical engineering practice are used in most landfill slope stability analyses. Some of the commercially available computer programs can be used to analysis slope stability, e.g., PCSTABL, SLIDE, SLOPE/W, etc.

In this paper, the slope stability was evaluated using PCSTABL, a well-accepted and reliable model used widely in the solid waste industry. This program uses two-dimensional limiting equilibrium methods to calculate a factor of safety (FS) against shear failure for slope sections analyzed. The program utilizes an automatic search routine to generate multiple shear failure surfaces for circular failure mode or block-type failure mode until the surface with the lowest FS-value is found. The analytical methods used for the circular (within waste mass) and block-type failure modes (along interfaces) in the slope stability analysis are the Modified Bishop and Modified Janbu methods, respectively. In this paper, only block-type failure mode is presented, since this scenario is the most critical failure mode when analyzing the interface shear strength and leachate level of a landfill bottom liner system.

In most waste slope stability evaluations and general industry standard, a FS of equal to or greater than 1.5 is considered acceptable for the static slope stability analysis of a waste slope. The veneer stability of the final cover system is not considered in this paper.

CASE STUDY

The goal of this case study is to identify potential instability issues due to presence of certain weak interfaces within the bottom liner system as well as due to potential high leachate level above the bottom liner system. Where the calculated factor of safety is below the acceptable value of 1.5, a solution is presented and demonstrated by selecting appropriate construction materials that have a greater interface shear strength to yield a higher factor of safety against slope instability. A sketch showing a typical waste slope profile modeled for this study is presented in Figure 1.

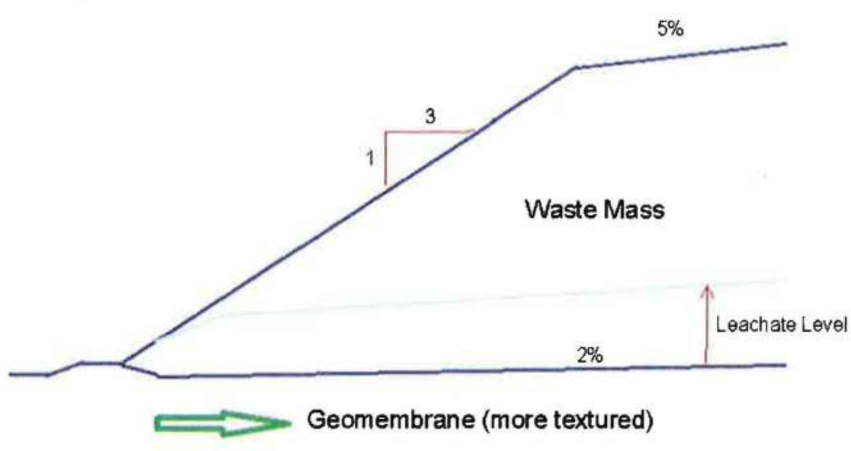

Figure 1: Typical Waste Final Slope Profile

The final slope was modeled at 1(V) to 3(H) and the landfill floor is at 2%. The inner toe of the landfill floor is about 3m below the crest of the perimeter containment berm. The maximum waste height above the top of the bottom liner system is 70m. The key shear strength and density assumptions for MSW waste and typical soil subgrade materials are provided in Table 2.

Table 2. Waste and Soil Shear Strength Parameters

Layer	In-Situ Density (KN/m^3)	Shear Strength Parameters	
		Friction Angle (deg)	Cohesion (KPa)
Waste	9.42	30	12
Foundation Soil	18.85	35	19
Final Cover System	18.06	28	2

RESULTS AND DISCUSSION

The factors of safety calculated using various interface types and their corresponding critical interface shear strengths for the above-mentioned slope section configurations are listed in Table 3. As shown in Table 3, a smooth geomembrane interfaced with a saturated and cohesive soil would give a much lower factor of safety when compared with the result using a textured geomembrane. In general, the factor of safety increases when the critical interface shear strength used in the analysis is stronger. This information is useful when deciding and selecting construction materials for a known landfill final slope configuration.

Table 3. Effect of Interface Shear Strength on Factor of Safety

Layer	Interface Friction Angle (deg)	Factor of Safety
HDPE-S/Cohesive Soil, Saturated	11	1.28
HDPE-S/Geocomposite Drainage Net (GDN)	15	1.50
HDPE-T/Cohesive Soil, Saturated	18	1.65
HDPE-S/Granular Soil	21	1.81
HDPE-T/Geosynthetic Clay Liner (GCL)	23	1.92

The effect of using certain amount or length of textured geomembrane (measured from the toe of the slope) was evaluated when considering the benefit of realizing a stronger available interface shear strength for a higher factor of safety. The results are presented in Table 4. By using approximately 100m of textured geomembrane, the factor of safety is increased from 1.28 (with 0m of textured geomembrane) to 1.58.

Table 4. Effect of Length of Textured Geomembrane on Factor of Safety

Textured Geomembrane on Cell Floor, Measured from Toe[1] (m)	Factor of Safety
0	1.28
30	1.34
60	1.42
100	1.58
All	1.65

1 - "0" means all smooth and "All" means all textured geomembrane.

The effect of leachate head on liner was evaluated for the above referenced slope profile using various leachate heads, from zero to 5m. The factors of safety calculated are shown in Table 5 for both smooth and textured geomembrane interfaces. The results clearly indicate that the factor of safety decreases with increasing leachte head on liner and the scenario of using textured geomembrane gives a higher factor of safety when compared that with the smooth geomembrane scenario.

As shown in Table 5, the factor of safety of 1.5 or greater can be achieved for the textured geomembrane scenario when the leachate head on liner is at or less than 5m.

Table 5. Effect of Leachate Level on Factor of Safety

Leachate Level Above Liner (m)	Factor of Safety	
	Smooth Geomembrane (Friction Angle = 11 deg)	Textured Geomembrane (Friction Angle = 18 deg)
0	1.28	1.65
0.3	1.27	1.63
1.0	1.25	1.60
3.0	1.20	1.53
5.0	1.08	1.50

For the case study of using 100m of textured geomembrane, measured from the toe of the perimeter berm toward the cell floor, the results are shown in Table 6. At zero and 0.3m leachate head on liner, the factors of safety calculated are 1.58 and 1.56, respectively. These factors of safety are above the required 1.5, including when the leachate head is at 1.0m. However, the factor of safety will be less than unity if the leachate head is more than 10m, indicating slope failure situation.

Table 6. Case Study - Effect of Leachate Levels on Factor of Safety

Leachate Level Above Liner[1] (m)	Factor of Safety
0	1.58
0.3	1.56
1.0	1.53
3.0	1.46
5.0	1.36
10.0	1.03

1 – 100m Textured Geomembrane with Interface Friction Angle = 18 degrees

CONCLUSION

This paper presents the sensitivity evaluation of two major parameters used in a landfill waste slope stability during landfill operations and final slope configurations. These key factors are:

- Weakest interface shear strength of the bottom liner system
- Presence of leachate head above the bottom liner system

The results of this evaluation illustrate the importance of knowing how much leachate head is allowed on the bottom liner system. It is possible to determine how much textured geomembrane is needed (for those landfills that used exclusively smooth geomembrane) to maintain a targeted factor of safety against slope instability and the maximum amount of leachate head on liner allowed without triggering instability of the landfill.

The methodlogy presented herein can be used for evaluating if the landfill operating or final slopes are likely to maintain a slope stability's factor of safety above 1.5, under certain leachate levels that are either measured in the field or by observation of sideslope seep locations. Site-specific slope stability modeling, taking into account actual slopes, material properties, liquid levels and other factors should always be performed for any landfill sites during design phase.

Because of the impact of leachate level on the factor of safety, the landfill operator should monitor the performance of the leachate collection system to confirm that the conditions assumed in the stability analyses are still valid, including liquid level measurements above the bottom of the landfill. It is also valuable to monitor the changes of these parameters over time, as they may serve as early indicators of potential problems. Since landfill operations may have a greater impact on slope stability than a closed landfill site, additional monitoring and controls should be implemented judiciously, such as landfill surface positive drainage and application of daily cover soil, to verify that landfill operations are not having an adverse impact on slope stability.

REFERENCES

Achilleos, Eftychios (1988). User Guide for PCSTABL5M. Joint Highway Research Project No. JHRP 88-19, School of Civil Engineering, Purdue University, West Lafayette, IN.

Koerner, George R. and Narejo, Dhani. Direct Shear Database of Geosynthetic-to-Geosynthetic and Geosynthetic-to-Soil Interfaces. Geosynthetic Research Institute, GRI Report #30, June 14, 2005.

Law, James. "Sanitary Landfill Mining – Operational Interim Slope Stability Aspects." 2013 Sardinia Symposium, Cagliari, Sardinia, Italy, September 30 – October 4, 2013.

Law, James, Isenberg, Robert, and Reed, Jeffrey. "Effects of Liquid Levels to Interim Slope Stability during Sustainable Landfill Practice." Global Waste Management Symposium sponsored by National Waste & Recycling Association and Environmental Research and Education Foundation, Orlando, FL, June 22-25, 2014.

Law, H. James. "Impact of Leachate Level above Liner System on Slope Stability during Landfill Operation." 2014 ISWA World Congress, Sao Paulo, Brazil, 8 – 11 September, 2014.