Stability of two landfills against sliding along interfaces of geosynthetics in base lining systems

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ABSTRACT: This paper describes the results of two separate case studies conducted to assess the stability of hazardous waste landfills against sliding along interfaces of geosynthetics in the base liner systems and highlights the influence of various parameters on the factor of safety. In case study A, the base was horizontal and the height of landfill was increased from 14.0 m to 31.8 m. As a consequence, sliding along the base became the critical failure surface for temporary waste slopes. In case study B, the base profile was governed by the bedrock level which was at a shallow depth below the ground surface. During the excavation, it became evident that the bedrock level exhibited significant elevation difference from one end to the other resulting in variable inclination of the base. The stability of the landfill against sliding along the interfaces of geosynthetics in the liner system was analysed for different conditions.
The studies highlight the influence of the following factors on the base sliding stability along soil–geosynthetic and geosynthetic-geosynthetic interfaces: (a) smooth versus textured geomembrane; (b) height of waste, (c) base inclination, (d) pore water pressures in wet waste, (e) leachate head, (f) seismic forces and (g) berm at the toe.
It is found that factors of safety are high when textured geomembranes are used, and when leachate head and pore water pressures are low and stabilizing berms are provided.

Keywords: Hazardous Waste Landfill, Stability, Sliding, Interface, Geomembrane

1 INTRODUCTION

Disposal of industrial and hazardous waste (HW) in engineered landfills is of prime importance in every industrial town in India. The efficacy of these landfills primarily depends upon the structural integrity and functional effectiveness of its containment system, i.e., its liner and cover system. The liner systems of HW landfills are typically composed of layers of compacted soil of low permeability overlain by geomembrane and other geosynthetics to prevent infiltration of leachate into the groundwater. Although geosynthetics have been widely used in landfills as a lining system, failure through their interfaces with clay and other geosynthetics is considered to be the primary cause of instability in landfills (Koerner and Soong 2000b, Filz et al. 2001, Bergado et al. 2006, Tano et al. 2016). This is attributed to low shearing resistance among the interfaces of geosynthetics and soil which results in potential sliding surfaces. Other contributing factors, such as high pore pressure in waste, generation of leachate head, weak foundation soil, etc. have also been found to trigger major slope failures in landfills (Seed et al. 1990, Koerner and Soong 2000b).

This paper describes two separate studies conducted to assess the stability of hazardous waste landfills against sliding along interfaces of geosynthetics and soil in the base liner systems. Among the interfaces between geosynthetics and soil present in the liner system, the critical interfaces are geomembrane-clay liner interface or geomembrane-geosynthetic clay liner interface below a smooth geomembrane, as well as geomembrane-geotextile interface or geomembrane-geocomposite interface above a smooth geomembrane. On the basis of widely reported values of interface shearing strength of the above-mentioned interfaces (Dixon et al. 2002, Bouazza et al. 2002, Triplett and Fox 2001, Wasti and Ozduzgun

2001, Jones and Dixon 1998), it was concluded that the interface among smooth geomembrane and clay liner is the most critical one; and thus, considered in both the case studies. In the first case, the base was horizontal and the height of landfill was increased from 14.0 m to 31.8 m. In the second case, the base profile was governed by the bedrock level which exhibited significant elevation difference from one end to the other. In both cases, stability of the landfill against sliding along the interface of geomembrane and clay liner in the lining system was analysed for different conditions and various influencing parameters.

2 CASE STUDY A

2.1 *Background*

A 14 m high HW landfill is under operation in the outskirts of an industrial town in western India. The underlying stratum consists of stiff to very stiff clay of high plasticity (CH). The SPT-N value varied from 11 at the top to 55 at 25 m depth. The groundwater level is at 9m depth. Total strength parameters of c=85 kPa and $\phi=4^o$ were obtained from Unconsolidated Undrained (UU) test.

The original capacity of the 14 m high landfill was 1,400,000 tons. As the original landfill approached its final height, the operator sought to enhance its capacity by increasing the height of the landfill to 31.8 m. Fig. 1 shows the initial section of the landfill for 14 m height and enhanced section of 31.8 m height. This increment in height would result in 35% increment in the holding capacity of the landfill. The details and consequent findings of the stability analyses performed on waste mass for the proposed increased height are presented in this study. Fulfilling the CPCB criteria for HW landfills in India (2001, 2002), the permanent waste slope profile consisted of 1V:4H slope for 31.8 m high waste mass with 3 m wide berms at every 8m height. For the temporary slope during filling of waste, inclination of 1V:3H was considered. The temporary waste slope was also 31.8 m high but with 2 m wide berm at every 8 m height.

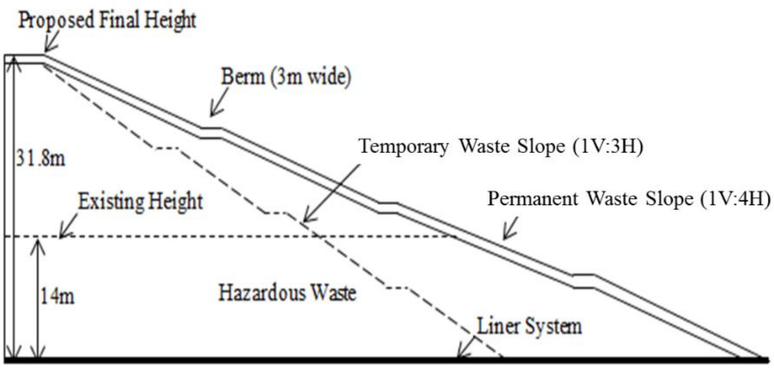

Figure 1. Sectional view of HW landfill, Case Study A

2.2 *Stability analysis*

2.2.1 *Methods of stability analysis*

The overall stability was assessed using the limit-equilibrium based slope-stability program SLOPE/W (Geo-Slope 2010). Morgenstern-Price (M-P) method was used to determine the critical slip surfaces and minimum values of factor of safety for two types of failure surfaces: (a) circular failure through the waste mass and (b) planar failure through waste mass and sliding along base liner system (two straight lines). The two typical failure surfaces are shown in Figures 2 and 3 in Sub-section '*Results*'. M-P method was chosen for the analyses as it is a rigorous method that considers both inter-slice shear and normal forces and satisfies both force and moment equilibrium.

2.2.2 *Conditions of analysis*

The permanent and temporary slopes of dry and wet waste were analysed for both static and seismic conditions. Pseudo-static method was used to analyse the seismic condition with horizontal acceleration coefficient α_H=0.1. The effect of leachate head (h) on the overall stability of the permanent and temporary waste slopes was also checked. Leachate head was modeled to simulate temporary clogging of leachate collection layer (LCL). The wet state of waste mass was modeled by assigning pore-water pressure ratio of 0.2 (Datta et al. 2017). In addition to the assessment of failure through waste mass, analyses were also carried out to consider the impact of weak interface between geomembrane and clay liner in the lining system at the base on the overall stability of the 1V:3H temporary waste slope. The weak interface was simulated with angle of interface shearing resistance of 10° between smooth geomembrane and clay. The improvement caused by replacing the smooth geomembrane in the weak interface with textured geomembrane (angle of interface shearing resistance = 24°) was assessed where smooth geomembrane resulted in inadequate stability.

2.2.3 *Materials and properties*

The parameters for the analysis of the waste slopes and interfaces are listed in Table 1. As the waste mass is composed of hazardous waste material, which is mostly inorganic in nature, the waste materials have higher unit weight and lower cohesion than municipal solid waste (MSW). The properties of subgrade soil were obtained from site investigation results. The minimum acceptable values of factor of safety (FoS) for various conditions are listed in Table 2.

Table 1. Material properties used in the stability analyses, Case Study A

Material	Unit Weight (kN/m^3)	Cohesion Intercept (kPa)	Angle of Shearing Resistance (°)
Materials used in stability analyses of waste mass			
Waste	16	3	25
Properties of Subgrade			
Subgrade Soil (Clay) Unsaturated	14	85	0
Saturated	18	0	24
Materials used in stability analyses of liner system			
Smooth GM-Clay Liner interface	-	0	10
Textured GM-Clay Liner interface	-	0	24

Table 2. Minimum acceptable values of FoS under different conditions of analysis

Conditions of Analysis	Acceptable FoS Permanent Waste Slope	Acceptable FoS Temp. Waste Slope
Dry Waste (r_u=0)	1.5	1.3
Wet waste /Rain/Seepage (r_u=0.2) (Short Term)	1.3	1.2
Temporary Clogging (Leachate head = 2 m) (Short Term)	1.3	1.2
Earthquake (Pseudo-static) (Very Short Term)	1.1	1.1
Rain/Seepage/Clogging + Earthquake (Very Rare)	1.05	1.05

2.2.4 *Results*

2.2.4.1 Failure through waste mass in permanent and temporary waste slope

The results of the stability analyses of permanent and temporary waste slopes of height 31.8 m for circular failure through the waste mass are summarized in Table 3. The results show that while both the permanent and temporary waste slopes are stable for all conditions of analysis, it is necessary that the leachate head in the temporary waste slope should be monitored carefully and not allowed to exceed 2 m; higher leachate head than 2m in the temporary slope of wet waste mass would result in fall in the value of FoS from 1.2 to less than acceptable value for the case of r_u=0.2 (static analysis).

2.2.4.2 Planar failure through waste mass and sliding along base liner in temporary waste slope

Table 4 presents the comparative results of sliding stability of waste along the smooth and textured geomembrane–clay interface in the basal liner. The results show that use of smooth geomembrane (δ=10°) results in unsatisfactory values of FoS for r_u=0.2 and h = 2m for static as well as for seismic conditions. When compared to corresponding results for overall stability in the temporary waste slope along circular failure surfaces, it was noted that stability of temporary waste slope is governed by sliding failure along the weakest interface of basal geosynthetic lining system. The values of FoS significantly increase with the use of textured geomembrane having angle of interface shearing resistance of 24°, as can be seen from the last column of Table 4. It was therefore recommended to use textured geomembrane at the base for all future landfill development. Figs. 2 and 3 show the critical sliding planes on smooth and textured geomembrane, respectively.

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Table 3. Results of stability analysis for circular failure through waste mass, (Case Study A)

Condition	1V:4H Waste Slope (Acceptable FoS)	1V:3H Waste Slope (Acceptable FoS)
Static Analysis, $r_u = 0$		
r_u=0, h=0 m	2.20 (> 1.5)	1.68 (> 1.3)
r_u=0, h=2 m	1.86 (> 1.3)	1.50 (> 1.2) (Figure 2)
r_u=0.2, h=2 m	1.71 (> 1.3)	1.20 (~ 1.2)
Seismic Analysis (Pseudo-static)		
r_u=0, h=0 m, α_H=0.1	1.44 (> 1.1)	1.23 (> 1.1)
r_u=0, h=2 m, α_H=0.1	1.28 (> 1.05)	1.11 (> 1.05)
r_u=0.2, h=2 m, α_H=0.1	1.07 (> 1.05)	-

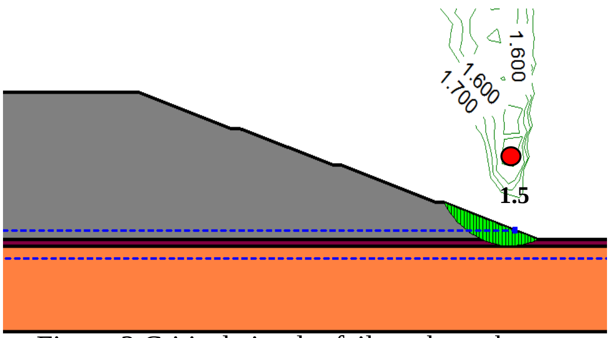

Figure 2 Critical circular failure through waste mass for 1V:3H waste slope on smooth geomembrane, h=2m

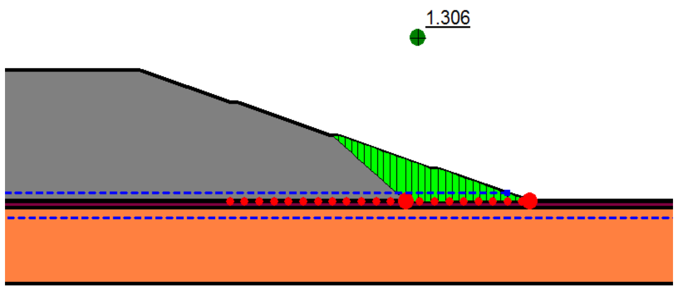

Figure 3 Critical planar failure through waste mass and sliding along base liner for 1V:3H waste slope on smooth geomembrane, h=2m

Table 4. Results of stability analysis for planar failure through waste mass and sliding along base liner (two straight lines) for 1V:3H temporary waste slope, (Case Study A)

Description	FoS (Comparision with Acceptable FoS)	
	Smooth Geomembrane (δ=10°)	Textured Geomembrane (δ=24°)
Static Analysis		
r_u=0, h=0 m	1.36 (> 1.3)	1.91 (> 1.3)
r_u=0, h=2 m	1.306 (> 1.2) (Figure 3)	1.81 (> 1.2)
r_u=0.2, h=2 m	1.04 (< 1.2)	1.48 (> 1.2)
Seismic Analysis (Pseudo-static)		
r_u=0, h=0 m, α_H=0.1	0.98 (< 1.1)	1.41 (> 1.1)
r_u=0, h=2 m, α_H=0.1	0.92 (< 1.05)	1.28 (> 1.05)

3 CASE STUDY B

3.1 *Background*

An engineered hazardous waste landfill is being constructed in phases in southern India. The base profile of the landfill is governed by the bedrock level which is at a shallow depth below the ground surface. During the excavation, it became evident that the bedrock level exhibited significant elevation difference from one end to the other, causing bed profile to be inclined. Figure 4(a) shows the section of the landfill. This study presents the details and consequent findings of the stability analyses performed on the waste mass resting on sloping ground, and its final stabilization with toe berm (Figure 4(b)).

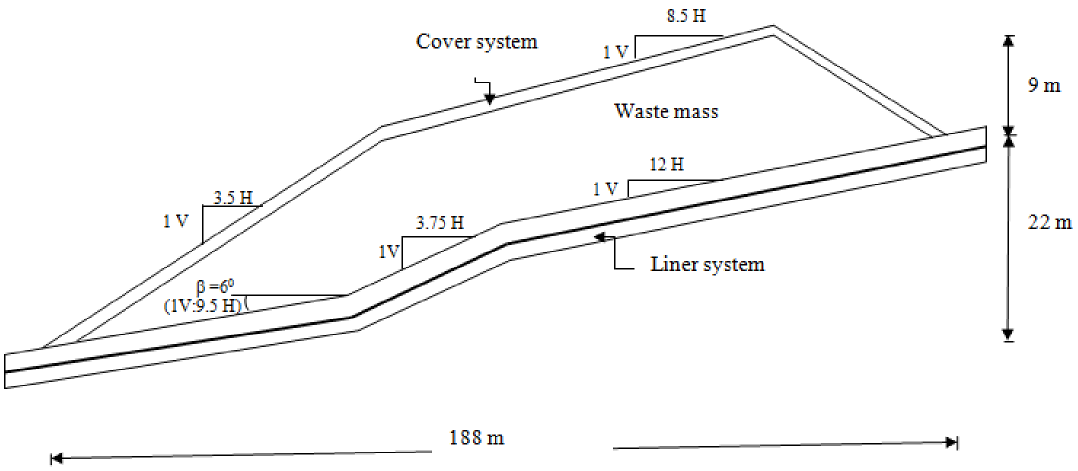

Figure 4 (a). Sectional View of HW landfill, Case Study B

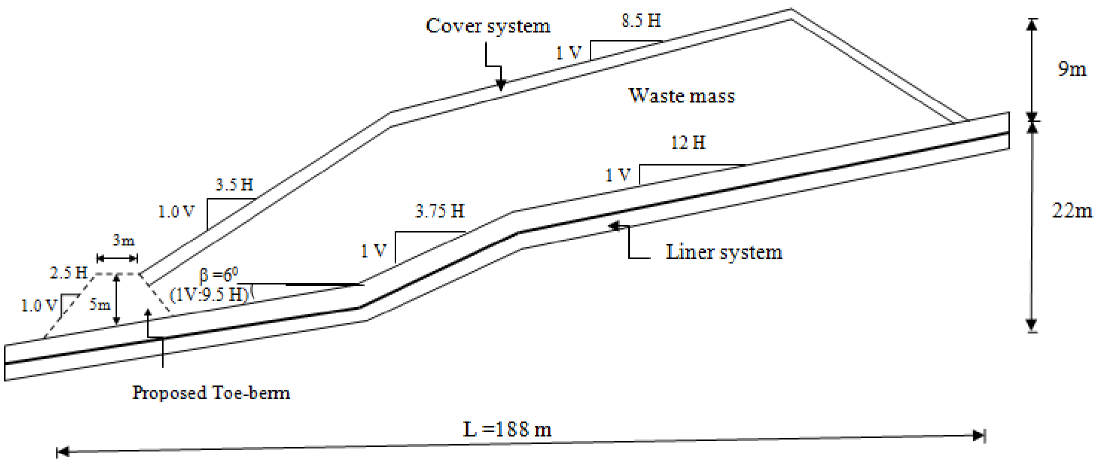

Figure 4 (b). Sectional View of HW landfill with proposed toe berm for stabilisation, Case Study B

3.2 *Stability analysis*

3.2.1 *Methods of stability analysis*

The stability of the landfill was checked against failure for three modes: (a) circular failure through the waste mass, (b) planar failure through waste mass and sliding along basal lining system (two straight lines), and (c) sliding along complete lining system at the base (from highest elevation to lowest elevation), under static and seismic conditions. The three typical failure surfaces are shown in Figures 5 to 7 in Sub-section '*Results*'. Similar to previous case study, Morgenstern-Price method was used to determine critical failure surface and minimum value of factor of safety (FoS). While failure through the waste mass was analysed using circular slip surfaces, failure due to sliding along complete lining system and planar failure through waste mass and sliding along lining system were analysed using straight-line slip surfaces. The case of sliding along the base considered the impact of weak interface between geomembrane and clay liner present in the lining system. Similar to Case Study A, the seismic condition was analysed by pseudo-static method (α_H=0.1).

3.2.2 *Conditions of analysis*

The base case considered for analysis comprised of cover slope of 1V:3.5H resting on an inclined base having β of 6° with smooth geomembrane in the liner system. This case was analysed for dry and wet waste for both static and seismic (pseudo-static method) conditions. The impact of varying the cover slope of the waste mass from 1V:3H to 1V:4H on the overall stability of the landfill was also investigated. Analyses were performed to check the influence of base inclination (β) from 0° to 9° on stability of dry waste mass of 1V:3.5H cover slope. The influence of pore water pressures in waste mass was investigated by varying the values of pore-water pressure ratio (r_u) from 0 to 0.2. The effect of strengthening the weak interface among geomembrane and clay liner was investigated in this case study similar to case study A. The interface between geomembrane and underlying clay in basal lining system was simulated with values of angle of interface shearing resistance ranging from 10° (smooth geomembrane) to 24° (textured geomembrane). As the landfill site is resting on inclined base, a berm was proposed at the toe of the landfill to enhance its stability; hence, the effect of berm at toe of landfill on the FoS was also assessed.

3.2.3 *Materials and properties*

The material properties used in this case study are given in Table 5.

Table 5. Material Properties used in the Stability Analyses, (Case Study B)

Material	Unit Weight (kN/m^3)	Cohesion Intercept (kPa)	Angle of Shearing Resistance (°)
Waste	16	3	25
Subgrade Soil	------Bedrock------		
Berm at toe	20	5	30
Smooth GM-Clay Liner interface	-	0	10
Textured GM-Clay Liner interface	-	0	18, 24

3.2.4 *Results*

3.2.4.1 Effect of inclination of base (β)

The effect of inclination of base (β) was investigated by varying its slope from 0° to 9° with 3° increments at every stage. For this set of study, waste was considered as dry, the cover slope of the waste mass was kept constant at 1V:3.5 H and only static conditions were analysed. Table 6 lists the results obtained from this study. For the three failure modes investigated in this set of study, the values of FoS varies linearly as the base inclination changes and the most critical value of FoS is observed in case of 9° base inclination. Among the three considered failure modes, planar failure through waste mass and lining system is observed to be the critical failure mode irrespective of the base inclination. Figures 5 to7 show the critical slip surfaces in the three failure modes for base inclination of 9^0.

Table 6. Results of stability analysis of dry waste mass with 1V:3.5 H outer slope and varying base inclination

Base inclination (β, °)	Circular Failure through waste mass	Planar Failure through waste mass and sliding along base	Sliding Failure along complete liner system in base
0	1.76 (>1.5)	**1.21 (<1.5)**	1.96 (>1.5)
3	1.69 (>1.5)	**1.10 (<1.5)**	1.62 (>1.5)
6	1.65 (>1.5)	**1.01 (<1.5)**	1.45 (<1.5)
9	1.61 (>1.5) (Fig. 5)	**0.88 (<1.5) (Fig. 6)**	1.34 (<1.5) (Fig. 7)

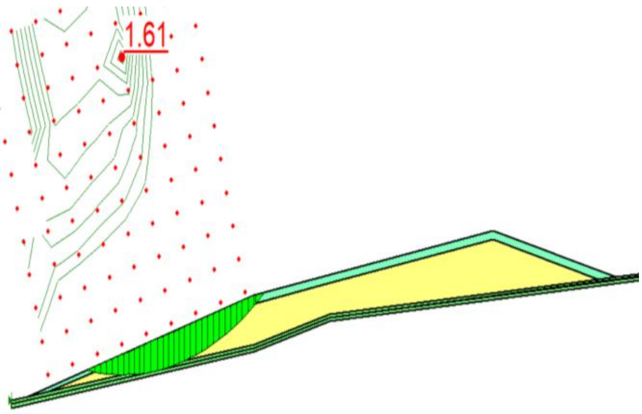

Figure 5. Critical circular failure through waste mass with $\beta=9^0$

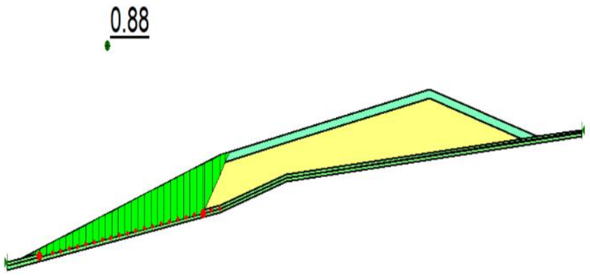

Figure 6. Critical planar failure through waste mass and sliding along base with $\beta=9^0$

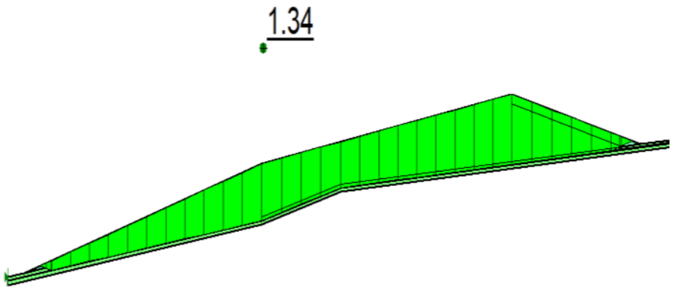

Figure 7. Sliding failure along complete lining system on base with β=9^0

3.2.4.2 Effect of cover slope

Analyses were carried out to check the influence of outer cover slope of waste mass on stability of the landfill. The cover slope was varied from 1V:3H to 1V:4H in two equal intervals. Similar to previous set of study, waste was considered as dry and only static conditions were incorporated while the inclination of base was kept at 6° as that of the landfill site. Table 7 lists the results of this set of study. It is observed that the cover slope has very little influence in the case of sliding failure along complete liner system, though it has major influence in circular failure through waste mass and planar failure through waste mass and sliding along lining system.

Table 7. Results of stability analysis of dry waste mass with 6° base inclination and varying cover slope

Cover slope of waste mass (V:H)	Circular Failure through waste mass	Planar Failure through waste mass and sliding along base	Sliding Failure along complete liner system in base
1:4.00	1.70 (>1.5)	**1.08** (<1.5)	1.46 (<1.5)
1:3.50	1.54 (>1.5)	**1.01** (<1.5)	1.45 (<1.5)
1:3.00	1.48 (<1.5)	**0.87** (<1.5)	1.43 (<1.5)

3.2.4.3 Effect of pore water pressure

To investigate the influence of pore water pressures in waste mass under static condition, the value of pore-water pressure ratio (ru) was assigned as 0.0 and 0.2. The inclination of base of the landfill was considered as 6° and the cover slope of waste mass as 1V:3.5H. The results are shown in Table 8. It is observed that presence of pore water pressure in the waste triggers instability in the landfill in all the three modes of failure considered in the study. The FoS changes significantly for all the modes of failure, and planar failure along waste mass and sliding along liner system is the most critical failure mode.

3.2.4.4 Seismic analysis

To investigate the influence of seismic forces, seismic analysis was conducted using pseudo-static method. This method uses horizontal and vertical seismic acceleration coefficients to simulate the condition of earthquake. The results are listed in Table 8. It is observed that FoS values in all the three failure modes reduce drastically in seismic condition; and for α_h= 0.1 and α_v= 0.07, all the failure modes become unstable. Among the three, the most critical mode of failure is observed to be the planar failure along waste mass and sliding along liner system.

3.2.4.5 Effect of strengthening of weak interface in liner

The results for analyses to investigate the effect of strengthening the weak interface between geomembrane and clay liner are given in Table 8. The strengthened interface in basal lining system was simulated with values of angle of interface shearing resistance (δ) as 18° and 24° (textured). It is observed that the use of textured geomembrane in the lining system significantly increases the value of FoS. While the landfill becomes stable under static and seismic condition for both the cases of textured geomembrane when the waste is dry, it becomes unstable for wet waste (r_u=0.2) even with textured geomembrane of δ=24° under both static and seismic condition. It is also observed that critical mode of failure for all the cases with textured geomembrane having δ=24° is circular failure through waste mass, rather than planar failure through waste mass and sliding along base as observed for cases with smooth geomembrane. Figure 8 shows the critical slip surface for circular failure through dry waste mass for textured geomembrane with δ=24° under static condition.

Table 8. Results of stability analysis of waste mass with 6° base inclination and 1V:3.5H cover slope under various conditions, (Case Study B)

Description	Circular Failure through waste mass	Planar Failure through waste mass and sliding along base	Sliding Failure along complete liner system in base
Static Condition, Smooth Geomembrane (δ=10)			
$r_u=0$, $\alpha_h=0$, $\alpha_v=0$	1.54 (>1.5)	**1.01 (<1.5)**	1.45 (<1.5)
$r_u=0.2$	1.22 (<1.3)	**0.77 (<1.3)**	1.15 (<1.3)
Seismic Condition (Pseudo-static method), Smooth Geomembrane (δ=10)			
$r_u=0$, $\alpha_h=0.05$, $\alpha_v=0.03$	1.28 (>1.1)	**0.83 (<1.1)**	1.00 (<1.1)
$r_u=0$, $\alpha_h=0.1$, $\alpha_v=0.07$	1.08 (<1.1)	**0.70 (<1.1)**	0.75 (<1.1)
Static Condition, Textured Geomembrane			
$r_u=0$, $\delta=18$	1.68 (>1.5)	**1.50** (~1.5)	2.64 (>1.5)
$r_u=0$, $\delta=24$	**1.75** (>1.5)	1.87 (>1.5)	3.6 (>1.5)
$r_u=0.2$, $\delta=24$	**1.19** (<1.3)	1.22 (<1.3)	2.19 (>1.3)
Seismic Condition (Pseudo-static method), Textured Geomembrane			
$r_u=0$, $\alpha_h=0.1$, $\alpha_v=0.07$, $\delta=18$	1.18 (>1.1)	**1.17** (>1.1)	1.38 (>1.1)
$r_u=0$, $\alpha_h=0.1$, $\alpha_v=0.07$, $\delta=24$	**1.23** (>1.1)	1.32 (>1.1)	1.89 (>1.1)
$r_u=0.2$, $\alpha_h=0.1$, $\alpha_v=0.07$, $\delta=24$	**0.98** (<1.1)	1.04 (<1.1)	1.51 (>1.1)
Static Condition, Textured Geomembrane, Stabilisation with Berm at Toe			
$r_u=0$, $\delta=24$	**1.99** (>1.5)	2.13 (>1.5)	3.83 (>1.5)
$r_u=0.2$, $\delta=24$	**1.87** (>1.3)	2.04 (>1.3)	3.73 (>1.3)
Seismic Condition (Pseudo-static method), Textured Geomembrane, Stabilisation with Berm at Toe			
$r_u=0$, $\alpha_h=0.1$, $\alpha_v=0.07$, $\delta=24$	**1.37** (>1.1)	1.41 (>1.1)	1.90 (>1.1)
$r_u=0.2$, $\alpha_h=0.1$, $\alpha_v=0.07$, $\delta=24$	**1.09** (>1.05)	1.16 (>1.05)	1.52 (>1.05)

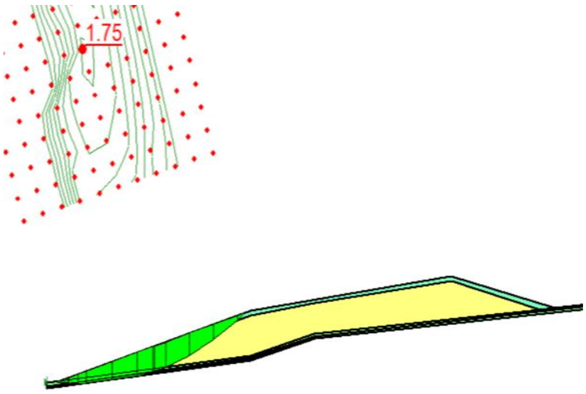

Figure 8. Critical Circular failure surface through waste mass, Textured Geomembrane (δ=24°)

3.2.4.6 Effect of berm at toe of landfill

Since the landfill on sloping base becomes unstable with wet waste even when textured geomembrane with δ=24° is used, a berm of 5 m height and 1V:2.5H slope is provided at the toe of the landfill while keeping the waste boundary unchanged (Figure 4(b)). The berm, which is usually built at the toe of the landfill and constructed with compacted soil or reinforced earth can increase landfill stability (Qian and Koerner 2009). The berm stabilized the landfill with wet waste mass for both static and seismic condition as is evident from last four rows of Table 8, where FoS for all failure surfaces are observed to be above the minimum acceptable values.

4 CONCLUDING REMARKS

This paper presents two case studies of assessment of stability of hazardous waste landfills against sliding along interfaces of geosynthetics in the base liner systems. The results highlight the fact that stability against sliding along base liner is low when height of waste is high, smooth geomembrane is used and base is inclined as well as when earthquake forces, pore water pressures or leachate heads are high. Use of textured geomembrane is found to overcome the stability problem in the case of horizontal bases. However, if the base has slight inclination, toe berm is required in addition to a textured geomembrane. Thus, it is concluded from the two case studies that factors of safety are high when textured geomembranes are used, and when leachate head and pore water pressures are low and stabilizing berms are provided.

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