Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-413

Stability and Sensitivity Analyses of an Industrial Waste Landfill with a Novel Final Cover System

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ABSTRACT

A stability analysis was carried out for a novel final cover system adopted by a paper packaging industry in Obbola, Sweden, and was analysed for veneer failure along geosynthetic interfaces. The landfill was used to store industrial waste generated from the paper mill industry between 1970 and 2006. The novel cover system was made from in-house industrial by-products and locally available materials such as: compost as vegetation layer, bio ash, compost and local excavated soil as protection layers, shredded tyres as drainage layer and green liquor dredge mixed with rock dust as barrier layer. The cover was analysed as both finite and infinite slope for standard static cases and for cases with destabilizing forces of earthquake and seepage build-up on the cover system. Based on the results obtained for different values of interface friction angle along the geosynthetic, minimum interface friction angle required for stable slope was back calculated. The variation of the interface angle required with the slope of the landfill was also analysed. Further, the landfill cover system was numerically modelled to compare the analytical and numerical results. The analytical method for all cases yielded a lower value of factor of safety than the numerical results. It was demonstrated that the software used in the study did not take into account the effect of interface friction angle for analysis of slope stability of the cover system. A method for incorporating the effect was also explored which showed good agreement with analytical results.

Keywords: Sustainability, Landfill cover, Alternative cover system, Slope stability, Factor of Safety

1 INTRODUCTION

Over the past decades, the cover systems for municipal solid waste (MSW) landfills have advanced from simple soil caps to multi-component systems that offer better control over infiltration and landfill gas (LFG) emissions. There has been a recent increase in the development of alternative cover systems that address the issues with conventional covers, such as high costs for construction and maintenance, vulnerability to damage from desiccation cracking, and inadequate control of LFG emissions. Under this umbrella, sustainable cover systems that use compatible waste materials with similar or improved hydraulic properties have garnered wide acceptability as these reduce the burdens on virgin natural resources and provide means for utilization of waste streams. It is prudent to mention here that while the conventional cover systems are seldom provided without geosynthetics, use of the same in alternate cover systems is sporadic at best. Geomembranes are HDPE impermeable membranes that are underlain by the drainage layer to further reduce the possibility of infiltration of rainwater into the landfill. These are frequently associated with geotextiles (woven or non-woven) that are used to increase the frictional resistance of the interface and provide a cushioning effect to prevent puncturing of the geomembrane by angular drainage layer particles. Further, despite the advantages offered by alternative covers, there have been several instances of veneer cover failures because most of the research on the development of these covers is focussed on hydraulic performance of the materials while the veneer slope stability has not been examined thoroughly.

Slope failure of conventional landfill cover systems has been studied by several researches since the 1980sand it is widely accepted and proved in laboratory as well as the field, that translational failure at an interface between two dissimilar materials, especially when geomembranes are present, is the main reason for landfill cover instability. The majority of the analytical techniques for stability against this kind of failure use two wedge theory or its variations (Martin and Koerner 1985; Giroud et al. 1995a; Ling and Leshchinsky 1997; Koerner and Soong 1998; Qian and Koerner 2010; Fox 2021a) while a lesser number of techniques use three or more wedges, enabling the analysis of failure geometries with broader applicability (Qian and Koerner 2009, Fox 2021b). Koerner & Hwu (1991) introduced an analytical method to evaluate the stability of geosynthetic-soil layered systems on slopes by defining the factor of safety as the ratio of assumed and mobilized values of interface strength parameters. Giroud et al. (1995a) simplified this using the limit equilibrium method and considering material properties, interface and geometrical characteristics. Giroud et al. (1995b) calculated the sliding factor of safety of the cover soil layer under three conditions of water flow in the drainage layer and proved that the flow thickness is an important parameter affecting the stability of the cover system. Koerner & Soong (1998) also calculated the sliding factor of safety of cover soil under the action of seepage in a drainage layer using the limit equilibrium method, with both investigations using the classic two-wedge sliding model. Soong & Koerner (1996) analysed the slip failures of the cover soil layer under seepage effect, constructing two analysis models and discussing the impact of size and material on slope stability. Feng & Gao (2012) developed a novel method to evaluate the seismic stability of a uniform landfill cover system under different seepage conditions. Khoshand et al. (2018) assessed the stability of the reinforced tapered landfill cover system with seismic forces under different seepage conditions based on Feng & Gao (2012). Nadukuru et al. (2017) numerically evaluated the impact of drainage conditions on slope stability of a landfill cover system by combining transient seepage and slope stability analysis. In these studies, it was established that the soil layer, located above the drainage layer, is identified as the most vulnerable part in the cover system. While these methods have been extensively applied for determining the stability of conventional cover system, it must be noted that the case studies on stability analysis of alternate cover systems based on these methods is scarce.

Based on the above discussion, in the present study, an analysis of veneer failure along the interfaces of geotextile provided above and below the drainage layer was carried for the case study of a small industrial waste landfill in Northern Sweden that was capped with a novel cover system based on the analytical method introduced by Koerner and Soong (2005). Analytical study of the cover slope was performed by considering the cover system as a finite and an infinite slope. For the finite slope, besides the standard case (without external load), analysis for cases with destabilizing forces of seepage build-up and earthquake forces was also performed. Further, a numerical model of the cover system was developed in Slope/W module of GeoStudio for i) infinite slope ii) finite slope iii) finite slope with seepage build-up and iv) finite slope with seismic loads. In order to study the effect of the angle of interface friction between the geotextile interface and the materials in its contact, the geotextiles in the numerical model were modelled by two methods: i) as reinforcement and ii) as a 10 mm layer. The results were compared and some of the disadvantages of using black box systems with limited transparency of the internal workings were highlighted.

2 MATERIALS AND METHODS

2.1 Description of the site

The landfill taken up in the present study was owned by a packaging paper industry in Sweden and utilized as a storage site for waste materials generated by the company, primarily, bark, ash, slag, mesa (calcium carbonate), recycled fibre waste, rock dust, green liquor, lime, and other waste. Landfilling was done for a period of 35 years from 1970 to 2006 following which, the landfill was closed using a sustainable alternative final cover, constructed in small areas, between 2006 and 2020 (Nordmark & Lagerkvist, 2007; Omari & Bodulla, 2012). The side slope of the landfill was 1:4, and groundwater level remained close to the ground surface throughout the year.

2.2 Materials

The following materials were used in the construction of the alternative cover at Obbola landfill (Nordmark & Lagerkvist, 2007; Omari & Bodulla, 2012): i) Vegetation re-establishment layer: compost, ii) Protection layer: three sublayers of local excavated material, compost and bio-fuel ash (BA), iii) Drainage layer: shredded tyre scraps (TS) and iv) Barrier layer: green liquor dredge (GLD) mixed with rock dust (RD) in 60:40 proportion. The cross-sectional profile of the landfill cover constructed has been represented in Figure 1. Omari & Bodulla (2012) conducted direct simple shear tests on the materials constituting the layers at the landfill to determine their shear strength parameters, along with basic geotechnical properties (reproduced in Table 1). These properties were used for validation of the numerical model. However, it was observed that the values of bulk density of the cover materials reported by them are too high and on cross examination, it was surmised by the authors that the values of bulk densities reported were more likely to be the saturated densities of the materials. Therefore, in further calculations, this correction was made while the bulk densities were back calculated from data as given in Table 2. Further, the cover had two geotextile layers designated as GTX_1, between the protection layer and drainage layer, and GTX_2, between the drainage layer and the barrier layer, forming four interfaces (top and bottom of each geotextile). The properties of the geotextiles are given in Table 3. These values were employed in the calculation of factor of safety both in analytical method as well as the numerical model. It must be noted that in their study, Omari & Boddula (2012) had assumed the values of interface friction of these geotextiles from literature and it has been concluded later in the study that this practice is erroneous and unreliable.

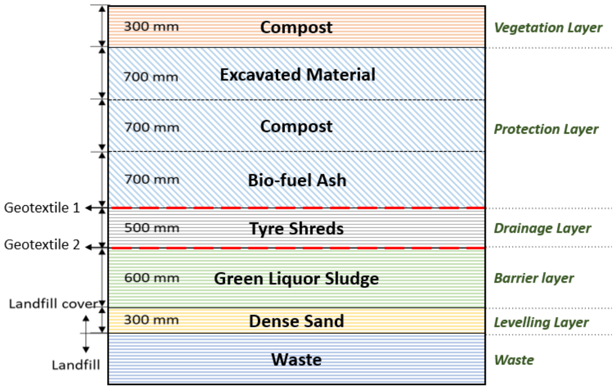


Figure 1.*Cross-sectional profile of Obbola landfill cover (Nordmark & Lagerkvist, 2007)*

Table 1. *Properties of landfill cover materials (as reported by Omari & Boddula, 2012)*

Material	c (kPa)	ϕ (degrees)	γ_{bulk} (kN/m^3)	Reference
Compost	0	21.78	16.32	Experimentally determined
Excavated material	0	32.70	14.20	Experimentally determined
Compost	0	18.28	16.37	Experimentally determined
Bio fuel ash	2.35	17.88	26.45	Experimentally determined
Tyre Shreds	0	37	10.79	Yang et al., (2002)
GLD: RD	1.06	15.13	23.87	Experimentally determined
Levelling layer	0	40	21.20	Das (1997)
Top waste	10	30	10.80	Landva & Clark (1990)
Bottom waste	30	20	15.41	Landva & Clark (1990)
Coarse sand	0	34	21.20	Das (1997)
Silty till	47.88	35	20.74	Bowles (1996)

c: cohesion; **ϕ:** Angle of internal friction; **γ_{bulk}**: Bulk unit weight of material; **GLD: RD**: Green liquor dust with rock dust

Table 2. *Corrected values of saturated and bulk densities taken in present study*

	Omari & Boddula (2012)				Corrected values		
Material	γ_{bulk} (kN/m^3)	γ_{dry} (kN/m^3)	w_n (%)	w_{sat} (%)	γ_{sat} (kN/m^3)	γ_{bulk} (kN/m^3)	γ_{dry} (kN/m^3)
Compost	16.3	6.9	121.3	135.5	16.3	15.3	6.9
Excavated material	14.2	7.4	46.4	91.9	14.2	10.8	7.4
Compost	16.4	6.8	88.7	140.1	16.4	12.9	6.8
Bio fuel ash	26.5	11.7	56.3	127.6	26.4	18.2	11.7
Tyre Shreds	10.8	10.6	-	-	10.8	10.8	10.6
Green liquor dredge with rock dust	23.9	14.8	26.2	60.7	23.9	23.9	14.8

γ_{bulk}: Bulk unit weight of material; **γ_{dry}**: Dry unit weight of material; **w_n**: natural water content; **w_{sat}**: Saturated water content; **γ_{sat}**: Saturated unit weight of material

Table 3. *Properties of geotextiles (Omari & Boddula, 2012)*

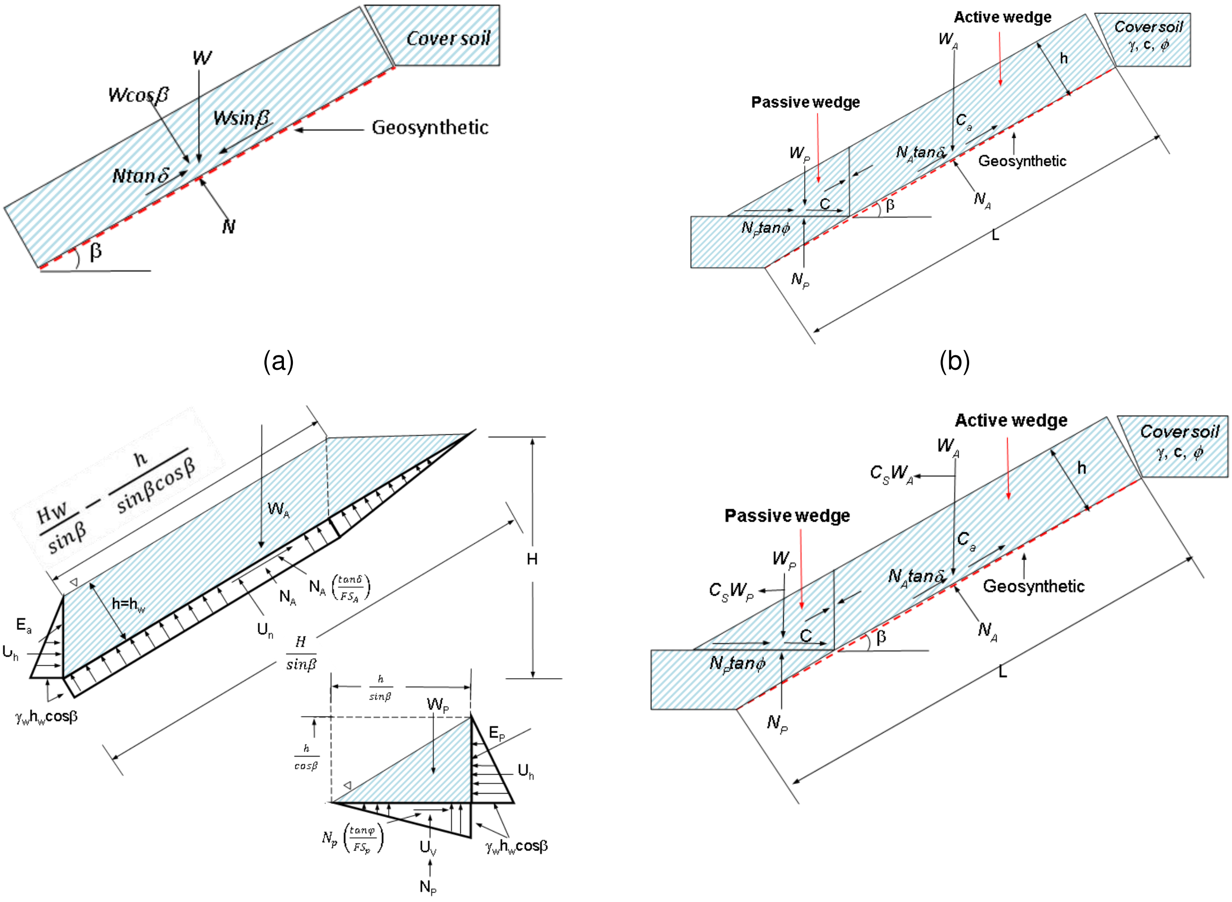
	Interface		Description	δ	Symbol	Reference
	Side	Symbol				
GTX-1	Top	*I_1*	BA-GTX$_1$	12.5°	δ_{BA}	Xu et al., 2008
	Bottom	*I_2*	GTX$_1$-TS	20 °	δ_{TS}	Reddy & Saichek 1998
GTX-2	Top	*I_3*	TS-GTX$_2$	20 °	δ_{TS}	Reddy & Saichek 1998
	Bottom	*I_4*	GTX$_2$-GLD	17 °	δ_{GLD}	Dixon-Jones et al., 1995

δ: Angle of interface friction between geotextile and overlying or underlying material

2.3 Methods

2.3.1 Analytical Program

The analysis of veneer failure of cover soil along the geosynthetic material interface was adopted from Koerner & Soong (2005) which is considered as a landmark paper in the field. The limit equilibrium method is usually used to analyze the stability of landfill cover systems. The interface between the soil and the geosynthetic serves as a clearly defined linear failure plane, and the cover soil is imagined to be a rigid block sitting on it (Ling and Leshchinsky 1997).



(a) (b)

(c) (d)

W$_A$: Total weight of the active wedge; **W$_P$**: Total weight of the passive wedge; **N$_A$**: Effective force normal to the failure plane of the active wedge; **N$_P$**: Effective force normal to the failure plane of the passive wedge; **β**: Soil slope angle beneath the geomembrane; **δ**: Interface friction angle between cover soil and geomembrane; **ϕ**: Angle of internal friction of the material; **c**: cohesion; **C$_a$**: Adhesive force between cover soil of the active wedge and the geomembrane; **L**: Length of slope measured along the geomembrane; **C**: Cohesive force along the failure plane of the passive wedge; **H**: Height of landfill from datum to top surface of cover; **h**: Thickness of the cover soil; **h$_w$** : height of free water surface perpendicular to the slope; **S$_r$**: Submergence ratio= hw/h; **D$_r$** : Depth ratio = H/h; **C$_S$**: Average seismic coefficient

Figure 2. *Free body diagram of (a) Case I (b) Case II (c) Case III and (d) Case IV (Koerner & Soong, 2005)*

For infinite slope analysis, the cover soil is assumed to form an infinitely long slope, and for finite slope, the toe end effects of the slope are considered. In the present study as two geosynthetic layers are present,cover soil slides with respect to the interface with the lowest friction angle in the underlying cross-section. For the present study, the factor of safety (FOS), calculated as the ratio of total resisting and destabilizing forces, was calculated for both upper and lower surfaces of the geotextiles, assuming that the anchorage of the geosynthetic at the crest is inadequate. The following cases for the analytical program were considered (Figure 2):

Case I - *Infinite slope without external loading*: Most of the studies for the slope stability of landfill cover systems analyse it as an infinite slope. In this case, the FOS along the geomembrane interface is calculated as the ratio of tangents of interface friction angle (δ) and slope angle (β). It can be seen in this case that the accuracy of FOS value in this case depends on the accuracy of measurement of friction angle between the cover material and the geosynthetic. The accuracy of the final results is directly dependent upon the accuracy of the laboratory interface friction value obtained. Moreover, this analysis is too simplistic for practical applications and cannot reflect the effects of forces that lower the FOS, such as seepage build-up and seismic conditions.

Case II - *Finite slope without external loading:* In order to incorporate more practical situations, finite analysis of the cover system was undertaken by incorporating a tension crack at the crest and a passive wedge at the toe of the slope that provides an additional resisting force to the slippage of the soil veneer (Figure 2**Error! Reference source not found.** (b)). In this case, there is no additional load on the cover m aterials and FOS is calculated only against the force of gravity.

Case III - *Finite slope with full seepage flow parallel to the surface:* This case may arise when the drainage layer overlying the geosynthetics is clogged up. In the present study, the geotextile used above and below the drainage layer can get blocked due to migration of fines. This can result in seepage forces on the particles due to water flow.

Case IV - *Pseudo static analysis of finite slope:* The pseudo static analysis of the cover is done by subjecting the centroid of the sliding veneer to a horizontal seismic force. The average seismic coefficient (C_S) of 0.1 is adopted after simulate severe earthquake (Rossi-Forel IX).

For the sake of brevity, complete analytical solutions have not been mentioned here and readers are advised to refer to Koerner and Soong (2005) for details on the methodology.

2.3.2 Numerical program

The numerical simulation of the landfill was performed in the SLOPE/W module of GeoStudio. The Morgenstern-Price method was selected for analysis of FOS as it considers both normal and shear forces between the slices and satisfies both force and moment equilibrium. The details of the simulation are given below:

Landfill geometry: A 2-D plane strain geometry was adopted for the analysis and owing to the symmetry of the structure, only half of the landfill was modelled. Besides the actual landfill slope of 1:4, the analysis was also carried out for slightly gentler (1:5) and steeper (1:3) slopes, to accentuate the effect of slope angle in the analyses undertaken in the study.

Material properties: The material properties adopted and experimentally determined by Omari & Bodulla (2012) were first simulated in SLOPE/W for validation purposes which showed good agreement as shown in Table 4. After validation, corrected properties of the materials, as given in Table 2 were used for analysis.

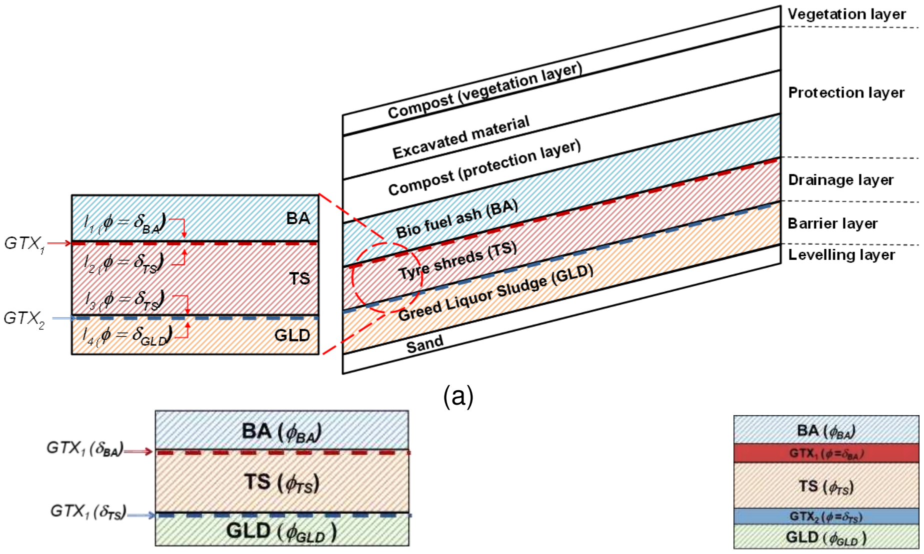
Table 4. *Validation of the proposed model based on FOS*

Slope	Omari and Boddula (2012)	Present study
1:3	1.25	1.18
1:4	1.62	1.56
1:5	1.96	1.97

Modelling of slope: For finite slope, entry and exit method was selected for defining the critical slip surface. The modelling of the infinite slope was done by using a fully specified slip surface parallel to slope and a tension crack line. This ensured uniform slice thickness including the first and last slice, which is a requirement for an infinite slope analysis (Krahn, 2004).

Modelling of geotextile: In GeoStudio, there is a provision for applying geosynthetics as reinforcements and the properties of the materials are primarily used for the calculation of pull-out resistance. However, this method does not take account of the effect of interface friction angle on the FOS. For this reason, the geotextiles were modelled by two methods. In the first method, the geotextiles were modelled as reinforcements as in standard procedure. The main inputs in this case were the interface adhesion and interface shear angle. In the second method, the geotextiles were modelled as layers of very small thicknesses as compared to cover layers (10mm) using Mohr-Coulomb model and the interface adhesion and friction angle were taken as the shear strength properties (Figure 3). The interface adhesion for all cases was assumed to be zero for conservative analysis. Both the interfaces of the geotextile i.e., top and bottom were analysed by using a fully specified slip surface at the top and bottom.

Additional forces: Pseudo static analysis was conducted by defining a seismic load with horizontal seismic coefficient (C_S) equal to 0.1. The cases of seepage parallel to the slope surface could not be modelled in the software due to insufficient information about the hydraulic properties of the cover materials.



(a)

(b)

(c)

Figure 3. *(a) Position and interfaces of geotextiles (b) Geotextiles modelled as reinforcement (c) Geotextiles modelled as layers*

3 RESULTS AND DISCUSSIONS

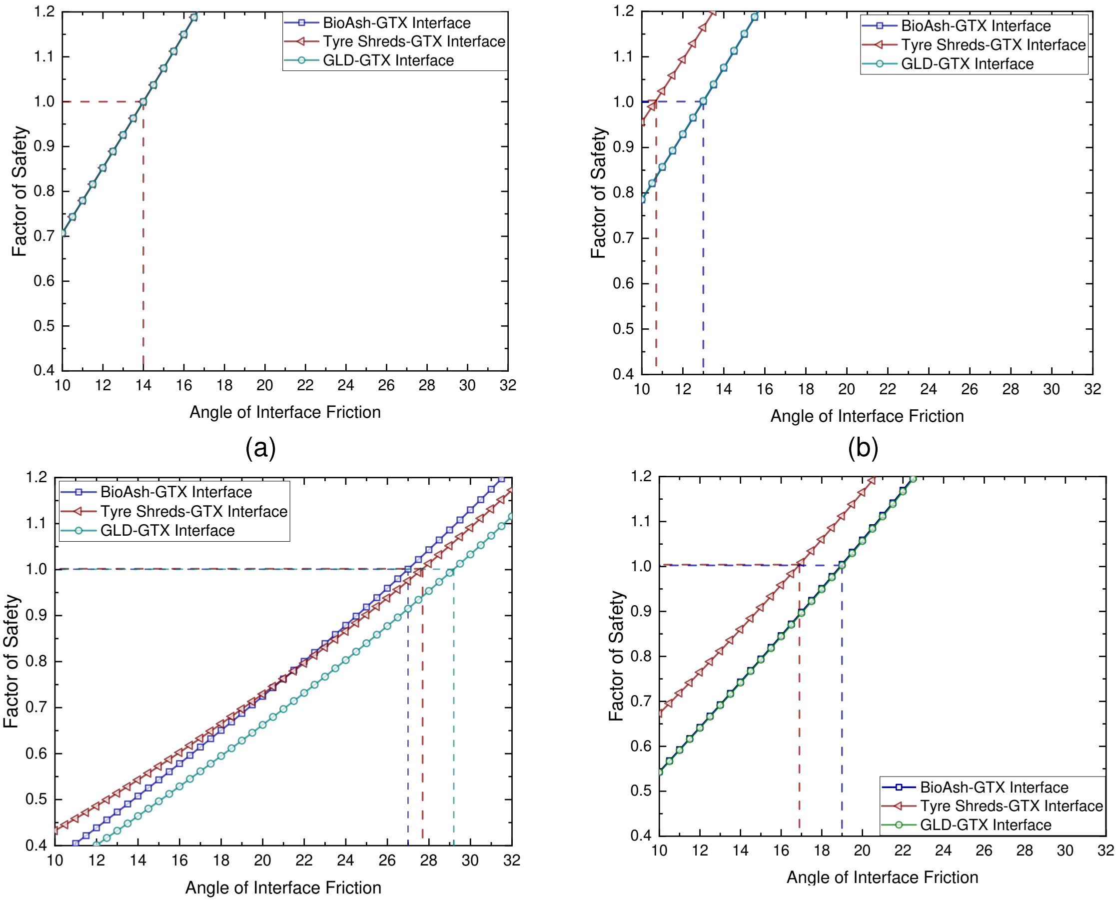
3.1 Analytical Results

The factor of safety obtained for the Obbola landfill for different cases are provided in Table 5. It can be seen that the analytical results for the FOS for standard cases (Case I & II) are lower than the values reported by Omari & Boddula (2012) from numerical modelling (Table 4) as well as the design requirement of 1.5. To accentuate the sensitivity of FOS to the interface friction angle, stability at 1:3 and 1:5 slopes was also analysed apart from the actual slope of the landfill (Figure 4 (e), (f)). For the sake of brevity, only the results for bioash-GTX_1 interface have been presented, while both interfaces showed similar trends. The minimum friction angle required for a stable slope in each case was determined from back calculation, by taking the limiting condition of FOS=1 (Figure 4) and the values were observed to be different for each case. This implies that even if the interface angle gives a safe FOS value in static conditions, the slope may fail due to external forces at the same interface friction. For instance, in Figure 4 (e) the minimum interface angle for limiting case of FOS=1 is 18°, however, during heavy rainfall on a cover system with clogged drainage layer (Case III), this value exceeds 32°.

Further, it can be seen that the absolute minimum friction angle required for a stable slope in static condition, for the Bioash-GTX_1 interface is 13 degrees, which is almost equal to the value taken by Omari & Boddula (2012) from literature. This implies that the cover system is on the verge of failure along this interface. Since the concerned landfill cover has performed well and no failure have been reported under external loads, it is safe to assume that the values taken by Omari and Boddula (2012) are too low. It must hence be noted that the value of interface friction angle is site specific and depends on the properties as well as in-situ conditions of the materials overlying or underlying it. Therefore, it must be experimentally determined for each case and taking values from the literature may lead to erroneous results. Furthermore, it was also observed that for all cases, the rate at which FOS decreases with decreasing angle of interface friction is higher in steeper slopes. This is important because lately more and more landfills are opting for steeper slopes as it provides higher waste acceptance capacity. Hence the slope of the landfill and the allowable interface friction angle must be selected with caution.

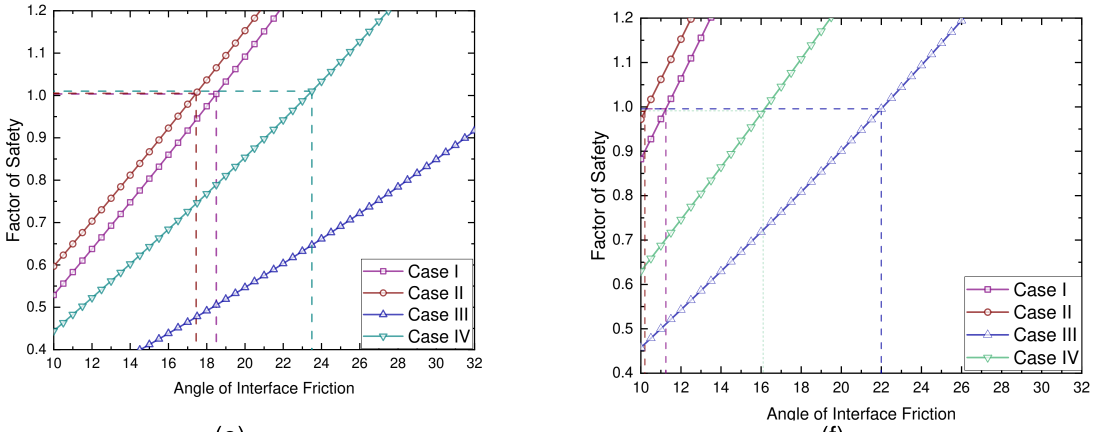
Table 5. *Analytical results of FOS for slope 1:4*

Interface	Values of FOS obtained using data from Omari & Boddula (2012)				
	Description	I	II	III	IV
I_1	BA-GTX	1	1.08	0.51	0.74
I_2/I_3	TS-GTX	1	1.23	0.54	0.86
I_4	GLD-GTX	1	1.08	0.46	0.6
	Minimum values of interface angle for each case based on analytical result				
	Case	I	II	III	IV
I_1	BA-GTX	14°	13°	27°	19°
I_2/I_3	TS-GTX	14°	10.7°	27.7°	17°
I_4	GLD-GTX	14°	13°	29.2°	19°



(a) (b)

(c) (d)



(e) (f)

Figure 4*. Variation of factor of safety with angle of interface friction for (a) Infinite slope (b) Finite slope (c) Finite slope with seepage parallel to slope surface (d) Finite slope with earthquake loads (e) Bioash-GTX$_1$ interface for slope 1:3 (f) Bioash-GTX$_1$ interface for slope 1:5*

3.2 Numerical Results

A comparison of FOS values obtained by analytical method and numerical modelling is presented in Tables 6-8. In case of infinite slope analysis, it can be seen from Table 6 that for numerical analysis, the value of FOS depends on the value of internal friction angle (ϕ) of the layer overlying the failure plane, irrespective of the thickness of the overlying layer. For reinforcement method, these values are ϕ_{BA} and ϕ_{TS} for GTX$_1$ and GTX$_2$, respectively (Figure 3). Hence, in this case, the values of interface friction angles (δ_{BA} and δ_{TS}) are not taken into account at all. For layer model, values of FOS for slip along top interface (*I_1 & I_3*) of geotextile match with the values obtained from reinforcement model. This is because the internal friction angles of the layers overlying the slip surface in both cases are same (ϕ_{BA} & ϕ_{TS} respectively). However, in layer model, when the bottom interface (*I_2 & I_4*) is taken as the slip surface, the internal friction angle of overlying material is the interface friction angle (δ_{BA} & δ_{TS}). The FOS values in this case match with the values obtained from analytical analysis. Thus, in order to account for the interface friction angle of the geosynthetic layer, the geosynthetic must be modelled as a separate layer and the bottom surface of the layer must be taken as the critical slip surface.

Table 6*. Comparison of results from analytical and numerical analysis for infinite slope (1:4) (Case I)*

Geotextile	Interface	Symbol	Analytical model		Numerical model			
					Layer model		Reinforcement model	
			δ	FOS	ϕ^a	FOS	ϕ^a	FOS
GTX$_1$	*I_1*	BA-GTX$_1$	δ_{BA}	0.89	ϕ_{BA}	1.59	ϕ_{BA}	1.59
	I_2	GTX$_1$-TS	δ_{TS}	1.46	δ_{BA}	0.89		
GTX$_2$	*I_3*	TS-GTX$_2$	δ_{TS}	1.46	ϕ_{TS}	3.01	ϕ_{TS}	3.01
	I_4	GTX$_2$-GLD	δ_{GLD}	1.22	δ_{TS}	1.46		

a: Value of internal friction angle of the material overlying the geotextile

For the numerical analysis of finite slope, it can be seen from Table 7 that the FOS values of veneer slope failure as calculated by analytical method are lower than the values obtained by numerical method. There is a percentage difference of 48% in the values of FOS for *GTX$_1$* and an 18% difference for *GTX$_2$* obtained from the two methods. Likewise, the comparison of results from pseudo static analysis obtained a percentage difference of 36% for *GTX$_1$* and 56% for *GTX$_2$* from the two methods (Table 8). It must be noted here that while in the analytical method, the critical slip surface is fully defined for both finite and infinite slope analysis, in numerical method, finite slope analysis was conducted by entry and exit method where the most critical slip surface was automatically selected by the software. It was observed that in this case, the critical clip surface passed through the protection layer (compost) and did not cross the geosynthetics at all. The reason for this discrepancy is that in this case, rotational failure has been assumed as opposed to translational failure because the software adopts a circular slip surface. This reinforces that a careful and thoughtful approach is necessary when selecting the values of FOS to be used in the design process. It is essential to exercise good engineering judgment, and relying solely on the numerical output of tools without a deep understanding of their internal workings may lead to inaccuracies.

Table 7. *Comparison of results from analytical and numerical analysis for finite slope (1:4) (Case II)*

Geotextile	Interface	Symbol	Analytical model		Numerical model	
					Layer model	Reinforcement model
			δ	FOS	FOS	FOS
GTX_1	I_1	BA-GTX_1	δ_{BA}	0.96	1.57	1.57
	I_2	GTX_1-TS	δ_{TS}	1.68		
GTX_2	I_3	TS-GTX_2	δ_{TS}	1.68		
	I_4	GTX_2-GLD	δ_{GLD}	1.30		

Table 8. *Analytical Comparison of results from analytical and numerical pseudo static analysis for finite slope (1:4) (Case IV)*

Geotextile	Interface	Symbol	Analytical model		Numerical model	
					Layer model	Reinforcement model
			δ	FOS	FOS	FOS
GTX_1	I_1	BA-GTX_1	δ_{BA}	0.74	1.07	1.07
	I_2	GTX_1-TS	δ_{TS}	0.86		
GTX_2	I_3	TS-GTX_2	δ_{TS}	0.86		
	I_4	GTX_2-GLD	δ_{GLD}	0.6		

4 CONCLUSIONS

In this study, numerical and analytical analysis was carried out on an industrial waste landfill for i) static case of infinite slope, ii) static case of finite slope, iii) finite slope with seepage build-up, and iv) finite slope with seismic forces. Two predefined slip surfaces were considered along the interfaces of two geotextile layers present on either surface of the drainage layer of the cover system. The effect of geosynthetic on veneer slope failure was assessed for both analytical and numerical methods. In the numerical model, the geotextiles were modelled by two means: i) as reinforcements (conventional) and ii) as layers. Based on the analysis, following conclusions were drawn:

- In case of slopes with geotextiles, the interface friction angle of the geotextile with respect to the underlying/overlying material should be calculated for each case and must not be taken from literature as it depends both on the slope of the landfill and in-situ conditions.
- For landfill covers, the slope of the landfill should be taken carefully because higher slopes increase the possibility of failure under adverse conditions. Steeper slopes for obtaining higher waste storage capacity should be avoided in areas prone to high rainfall and seismic forces.
- The FOS obtained from analytical results in all cases were lower than those obtained from numerical analysis. Despite the fact that analytical methods make a number of assumptions, in this study the analytical results were inferred to be more reliable. This follows from the fact that the software used for numerical modelling did not incorporate the effect of interface friction angle on the slope stability of the system when modelled conventionally (as reinforcements). It was demonstrated that in order to realise the effects of interface friction angles, the geotextiles can be modelled as thin layers of separate materials.
- When carrying out slope stability analysis using software, preferably, a comparison with analytical results should also be made if the internal workings of the software are not transparent.

5 FUTURE STUDY

The authors are currently working on comparison of translational failure of finite slope in the software using block failure with the analytical results obtained in this study. The reliability analysis using Monte-Carlo simulations to analyse the planar failure modelling of the landfill slope is also underway.

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The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 4, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.