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Safety factors comparison of landfill lining components using single & double interface shear strength results

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Abstract. The design of a competent basal lining system is crucial in ensuring a long-lasting and functional engineered municipal solid waste (MSW) landfill. However, due to the inclusion of numerous geosynthetics and geomaterials forming a multi-layered lining system, there rises an uncertainty on determining the critical or weakest interface. This is exacerbated by the different properties offered by these lining materials and their inter-crossing functions in landfills. According to ASTM D5321-20 standard, the interface shear strengths used in design of bases and side-slopes of lining systems are determined through a single interface testing configuration. However, minimal research has been done to evaluate the consequences of multi-interface testing configurations on the minimum factors of safety (FoS_{min}). The present study was thus conducted to further investigate this phenomena while establishing the appropriateness of double interface testing configuration using large direct shear equipment. It was found that, the difference in the FoS_{min} was insignificant for critical interfaces observed under single and double interface testing configurations.

1 Introduction

Engineered municipal solid waste (MSW) landfills have played a crucial role in protecting both human health and the environment [1]. Geosynthetics have increasingly been incorporated into engineered MSW landfill lining systems as they offer a cost-effective solution compared to geomaterials while ensuring a competent hydraulic barrier [2]. The purpose of an engineered MSW landfill is to achieve a maximum disposal capacity by increasing elevations, leading to steep slopes on sides and bases of MSW landfills [1]. As these geosynthetics and geomaterials are being introduced in the engineered MSW landfills' lining systems, their interaction becomes pertinent due to possible shear failure associated with inadequate designs due to lack of understanding of interface shear strengths [3]. Engineered MSW landfill failures have been well documented in these studies [4]–[6]. It was also commonly found that failure within an engineered MSW landfill mainly took place along the liner's base through landfill subgrades, side-slopes and sometimes through the waste mass

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itself. Therefore, it is imperative for landfill designers to understand all the failure dynamics and mechanisms during pre-construction, on-construction, and post-construction to avoid catastrophic failure of these sensitive geo-environmental structures [7].

In the laboratory, single interface shear strength tests of either soil-geosynthetic or geosynthetic-geosynthetic interactions in engineered lining systems are typically conducted as per ASTM D5321/5321M-20 [8]. This approach is widely accepted for various reasons, such as confidence in the determined results [9]. However, single interface testing configurations pose an uncertainty leading to overestimating of interface shear strength parameters due to specimen confinement [10]; while in most cases not simulating field characteristics of the liner arrangement, which is usually a composite of multi-layered lining systems [11]. The limitations of single interface shear testing can be controlled and captured in double interface shear testing which encapsulates soil-geosynthetic-soil, soil-geosynthetic-geosynthetic or geosynthetic-geosynthetic-geosynthetic [12].

In engineered MSW landfills two types of failure pose a critical threat, i.e., the basal lining system's translational failure and overall slope rotational failure, whose analysis is routinely implemented through limit equilibrium method (LEM) and finite element method (FEM), respectively. Translational failure mechanism focuses on assessing the internal stability of lining components of an engineered MSW landfill which includes the integrity of materials and waste interaction from the subgrade, the linings, and the solid waste itself. This method was adopted from a translational failure of a two-part wedge system as presented by [13]; and further modified to include the effect of apparent cohesion and adhesion by [14].

As a result, this study was conducted to assess the comparability of single and double interface shear strength results on a practical MSW engineered landfill design by determining minimum factors of safety (FoS_{min}). The design application assessment utilized in this study was for the basal lining system, which contained a multi-layered soil-geosynthetic and geosynthetic-geosynthetic interfaces. The study implemented the internal stability analysis on the side-slopes and bases of the proposed MSW landfill cell using LEM. The LEM was preferred due to several benefits over other analytical techniques including the ability to determine the magnitude and direction of the inter-wedge forces and the determination of lower bound (FoS_{min}) solutions [3]. Furthermore, this approach incorporated the apparent adhesion of lining components as some of the lining materials were highly reinforced and exhibited high apparent adhesion values that could not simply be ignored in the assessment of FoS_{min}.

2 Methodology

Establishment of the minimum factors of safety was implemented through a two-part wedge analysis reflecting a translational failure mode adopted from [3] and shown in **Figure *1***. This approach assumed that, within the waste mass, there exists a two-part wedge system that includes active and passive wedges. An active wedge causes failure on the side-slope that could either be lined or placed over the existing waste mass. However, a passive wedge overcomes this instability by providing sufficient resistance. The primary assumption of this approach, that fulfils the shear failure criteria, was that the average shear stress on the interface between active and passive wedges should not exceed the average shear strength available [13]. Equations used in determining the minimum factors of safety can be found in these studies [3], [13]–[15].

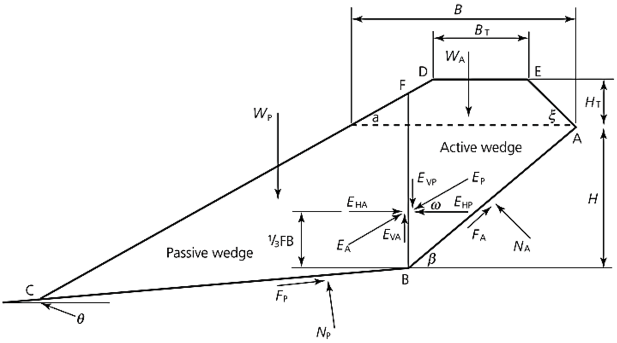

Figure 1: Acting forces within waste mass in a landfill cell [3]

2.1 Design Parameters

Table *1* summarises the geometric and inherent solid waste parameters used in the FoS_{min} assessment for the proposed MSW landfill. The interface shear strength parameters were determined through a series of single and double interface testing configurations using the large direct shear equipment known as *ShearTrac-III*®. The peak strengths were used at the base and large displacement (LD) strengths on the side-slopes of the proposed landfill cell. This is because the critical interface could be different at the base and side-slopes (or back-slopes) of the lining system since it is mainly influenced by the variability of waste depth and placement routines [3]. As a result, it could lead to unconservative FoS_{min} estimations if a landfill is lined with a multi-layered soil-geosynthetics components and only one type of strength for the critical interface is used for the stability analyses.

Table 1: Summary of geometric and inherent solid waste parameters

Parameter	Meaning	Value	Units
B	Width of the new waste mass at the level of the existing waste mass	35.0	m
C_{SW}	Apparent cohesion of solid waste	3.0	kN/m^2
H	Depth of existing waste mass/height of side-slope	30.0	m
α	The angle of the front slope, measured from horizontal, 3.5(H):1(V)	15.9	°
ϕ_{SW}	Internal friction angle of solid waste	30.0	°
γ_{SW}	Unit weight of solid waste	10.2	kN/m^3
β	The angle of the back slope, measured from horizontal, 4(H):1(V)	18.4	°
θ	The angle of landfill cell subgrade, measured from horizontal, 2%	1.1	°

Site and project-specific materials were used to determine the interface shear strength properties to achieve a good and relevant design. The lining system for the proposed landfill cell is shown in **Figure *2***. The geosynthetic lining components included two protection needle-punched nonwoven geotextiles with 2.6mm thickness (GTX-1) and with 4.4mm thickness (GTX-2), a 1.0mm fibre-reinforced nonwoven geotextile (GTX-3), a 2.0mm smooth HDPE geomembrane (GMB-1), a 1.5mm smooth LLDPE geomembrane (GMB-2) and a synthetic cuspated drain (CD). The geomaterials included leachate collection stone

(LCS), gravelly sand (GS) and sand; the USCS classification of the geomaterials was poorly graded gravel, poorly graded sand with some gravels and poorly graded sand, respectively.

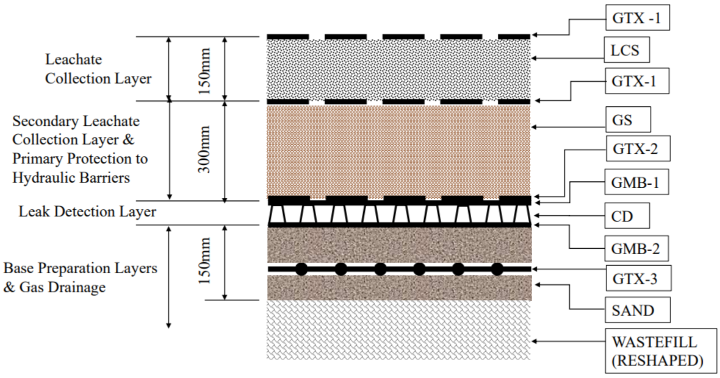

Figure 2: Proposed lining system for an engineered MSW landfill [16]

This study's interface shear strength parameters are seen in **Table *2*** and **Table *3*** for single and double interface testing configurations, respectively.

Table 2: Strength parameters for lining components tested under single interface configuration

No.	**Lining Arrangement**		**Peak shear strength, used at the base**		**LD shear strength, used at the side-slope**	
	Upper	**Lower**	δ_P [°]	$C_{P.}$ [kPa]	δ_A [°]	C_A [kPa]
1	LCS	GTX-1	26.40	0.00	15.46	0.00
2	GTX-1	GS	36.43	0.00	28.18	0.00
3	GS	GTX-2	38.08	13.32	35.50	0.00
4	GTX-2	GMB-1	11.27	4.30	9.37	0.00
5	GMB-1	CD	18.45	0.00	18.45	0.00
6	CD	GMB-2	24.04	9.27	24.04	9.27
7	GMB-2	SAND	29.07	0.00	22.74	0.00
8	SAND	GTX-3S1	37.71	24.66	36.99	24.66
9	GTX-3S2	SAND	32.21	44.99	30.42	0.00

Table 3: Strength parameters for lining components tested under double interface configuration

No.	**Lining Arrangement**			**Peak shear strength, used at the base**		**LD shear strength, used at the side-slope**	
	Upper	**Middle**	**Lower**	δ_P [°]	$C_{P.}$ [kPa]	δ_A [°]	$C_{A.}$ [kPa]
1	LCS	GTX-1	GS	44.74	0.00	44.02	0.00
2	GS	GTX-2	GMB-1	13.55	4.46	10.24	6.77
3	GTX-2	GMB-1	CD	13.40	14.80	10.59	0.00
4	GMB-1	CD	GMB-2	20.30	10.00	20.30	10.00
5	CD	GMB-2	SAND	24.51	0.00	23.99	0.00
6	SAND	GTX-3	SAND	31.11	85.71	31.11	85.71

3 Results & Discussion

The results of FoS_{min} are presented in **Table 4** and **Table 5** for single and double interface testing configurations, respectively. In the tables, nomenclature ‘a’ represents FoS_{min} determined on the active wedge i.e., the side-slope using LD interface strengths while ‘p’ represents FoS_{min} determined on the passive wedge i.e., the base using peak interface strengths. The numbers 1 to 9 and 1 to 6 represents interface arrangements on the single and double interface configurations, respectively. The following deductions were made regarding internal stability of the engineered MSW landfill’s basal lining system assessed using a translational failure mechanism through LEM.

- The lowest FoS_{min} value of 1.01 was determined on a single interface GTX-2 | GMB-1. Therefore, it can be deduced that the GTX-2 | GMB-1 interface was the weakest, and if failure were to occur, this interface would be the first to fail at both locations of the landfill, i.e., at the base and at the side-slope. Additionally, the highest value of FoS_{min} observed was 4.29, with the base interface being GS | GTX-2 and the side-slope interface being SAND | GTX-3S1. These two interfaces can also be considered the strongest under the single interface testing configuration.

For a double interface FoS_{min} evaluation, it was observed that an interface with GTX-2 and GMB-1 combination had the lowest FoS_{min} of between 1.17 to 1.19, as can be seen in

- **Table 5**. The highest FoS_{min} value of 5.42 was observed at the LCS | GTX-1 | GS interface, indicating that this interface was the strongest in both landfill locations, i.e., at the base and at the side-slope. Another double interface that recorded a higher value of FoS_{min} than those recorded by single interface configurations was SAND | GTX-3 | SAND interface, with 4.45 at the side-slope and 4.42 at the base.

It should also be noted that, the observation of a smooth geomembrane (GMB-1) with nonwoven geotextile (GTX-2) interface dictating the critical or weakest interface in the proposed basal lining system conformed to observations by other scholars including [11], [17]–[19].

Table 4: Minimum factor of safety for single interface testing configuration

Interface at back slope	1a	2a	3a	4a	5a	6a	7a	8a	9a
Interface at base	**Minimum Factor of Safety (FoS_{min})**								
1p	2.12	2.86	3.36	1.79	2.29	2.62	2.53	3.49	3.01
2p	2.75	3.51	4.02	2.41	2.92	3.26	3.18	4.15	3.66
3p	2.88	3.65	4.15	2.54	3.05	3.39	3.31	4.29	3.79
4p	1.32	2.03	2.51	1.01	1.48	1.80	1.72	2.64	2.17
5p	1.69	2.41	2.90	1.36	1.85	2.17	2.09	3.03	2.55
6p	1.99	2.73	3.22	1.66	2.16	2.49	2.40	3.35	2.87
7p	2.28	3.02	3.52	1.94	2.44	2.78	2.69	3.65	3.17
8p	2.86	3.63	4.13	2.52	3.03	3.37	3.29	4.27	3.77
9p	2.51	3.26	3.76	2.17	2.67	3.01	2.92	3.89	3.40

Table 5: Minimum factor of safety for double interface testing configuration

Interface at back slope	1a	2a	3a	4a	5a	6a
Interface at base	**Minimum Factor of Safety (FoS_{min})**					
1p	5.42	3.12	3.13	3.70	3.92	4.45
2p	3.32	1.17	1.19	1.71	1.91	2.40
3p	3.32	1.17	1.19	1.71	1.91	2.40
4p	3.70	1.52	1.53	2.07	2.27	2.77
5p	3.94	1.74	1.75	2.29	2.50	3.01
6p	4.42	2.18	2.20	2.75	2.96	3.47

4 Conclusion

Generally, it should be noted that during a landfill's operation, the only parameters that change are geometric ones, precisely the depth of the waste (H) and top width of the waste (B). As a result, the waste filling sequence should be suitably designed to suit FoS_{min} of 1.3 [20]. According to [3], these lower bound results may be directly applied to manage the design of the lining system due to their conservativeness. In this study, a worst-case scenario was considered where the H & B dimensions were overshot as the proposed MSW landfill cell was expected to operate for at least 15years. This led to achieving FoS_{min} of 1.01 on the GTX-2 | GMB-1 interface, which was the critical interface for the basal lining system of the proposed MSW landfill observed under single interface testing configuration. However, a similar interface was observed to be critical under double interface configuration as well.

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