

# Inversely Unstable – The Lining of Steep Landfill Slopes in South Africa

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## ABSTRACT

In South Africa and indeed globally, there is, and will be for the foreseeable future, a need for landfills for the final disposal of waste. Suitable sites for these landfills have become scarce, and as a result, even though they are more costly to engineer, sites with slopes greater than 1 in 4 are becoming more commercially viable. The design of lining systems for steep slopes however, poses significant technical challenges.

This paper discusses and presents the results of an investigation to determine the performance and stability of a Class B landfill lining system on various slope angles. The Class B landfill lining system was assessed in terms of the prescribed mineral layers, geosynthetic materials and alternatives of equivalent performance.

The factors of safety for stability on slopes of 1:4, 1:3, 1:2 and 1:1 using 2-D limit equilibrium analyses were calculated.

The results of the various factors of safety are presented, showing a distinct exponential relationship.

## 1. INTRODUCTION

In the recent decade, landfill liner stability and analysis have been brought to the forefront of landfill liner design due to the various minor and major failures experienced locally and internationally. We have heard from the experts themselves, in the likes of Dr. Koerner and Mr R. Thiel, about the variables to be considered in landfill liner designs, at previous Wastecons' and LIG Conferences. This paper does not intend to repeat their works, but to present my findings from research that was carried out on the various factors of safety achieved from using the prescribed mineral layers and/or alternative geosynthetics from varying, gentle to steep, landfill slopes.

During the design of various lining systems for different sites, the stability and integrity of the lining system is always in question. Although the National Norms and Standards for Disposal of Waste to Landfill provides the minimum requirements for the lining system and states that alternative design layouts for slopes exceeding 1:4 may be considered, the design Engineer is always left with the decision of what the optimum lining system would consist of and what the most desirable landfill side slopes should be taking into consideration the cost implications and whether the design is environmentally acceptable for the duration of its intended life.

Although every lining system design is site specific, the design of lining systems on steep slopes has and always will be a global challenge. Elton et al., 2002 paper which details geomembrane research needs states that further research is required on geomembranes on steep walls, thus the motivation for this research and paper.

The question thereafter arises, what is a steep slope?

The definition of a steep slope is often subjective and is often assumed to be near vertical. (Jones and Dixon, 2003) suggest that slope angles in excess of 30° are "steep". (Fowmes, 2007) suggests that the classification of steep sided landfill be based on the stability of the internal components, and the following definition of a steep slope is suggested and will be used for this dissertation:

"A steep slope lining system is a side slope lining system placed at an angle, at, or greater than the limiting value at which the geological barrier, drainage layer, or artificial sealing liners are naturally stable without application of additional loads from the waste mass, anchorage or engineered support structures." (Fowmes, 2007)

The general objective of a landfill design is to provide a cost effective, environmentally accepted waste disposal facility and the main objective of the lining system is to prevent pollution by leachate of the adjacent ground water and surface water. Therefore, the stability and integrity of the lining system on steep slopes, in both the short and the long term, are vital in its performance as a barrier.

## 2. SPECIFICATIONS OF PRESCRIBED LINING SYSTEM ELEMENTS

Every containment barrier design is made up of a series of liner components and depending on the Class of Landfill, must be arranged accordingly.

The liner components may include the following:

- a) Under drainage and monitoring system
- b) Base preparation layer
- c) Clay liner layer
- d) Geomembrane liner
- e) Protection layer
- f) Leachate collection layer
- g) Geotextile filter
- h) Leakage detection system

The detail associated with each liner component is described in the Minimum Requirements for Waste Disposal by Landfill (DWAf, 1998) and the variations are stipulated by the National Norms and Standards for Disposal of Waste to Landfill (Government Gazette, No. 36784, 2013):

A few of the above containment barrier components may be replaced with alternative elements of proven performance (Government Gazette, No. 36784, 2013), such as the replacement of:

- i) Granular filters or drains with geosynthetic filters or drains
- ii) Protective soil layers with geosynthetics
- iii) Clay components with geomembranes or geosynthetic clay liners

The use of the above alternatives raises the concept of Equivalency and the design-by-function concept must be adhered to and the construction factors, hydraulic factors and physical/mechanical factors need to be assessed accordingly.

### 2.1 Selection of Lining System to be Assessed

The selection of a representative lining system to be used for the assessment was difficult. Ideally a Class A landfill lining system as prescribed by the National Norms and Standards for Disposal of Waste to Landfill, which consists of a double composite liner, would have been useful as it contains all the possible interface interactions. However, due to the possible assessment of a geocomposite leakage detection system, which consists of a geonet between two geotextiles, the Class A landfill lining system was not selected. The ring shear apparatus used was unable to determine the interface shear of a geonet against a geotextile due to the large aperture/opening size of the geonet. Therefore a Class B landfill lining system was selected to assess the lining of steep landfill slopes. A Class B landfill lining system, when compared to a Class A landfill lining system, contains all the interface interactions that were encountered except for the following:

- i) A geotextile filter layer against a clay liner
- ii) A clay liner against a 2mm thick HDPE geomembrane

For the purpose of this research and paper a Class B landfill lining system was assessed and is shown below.

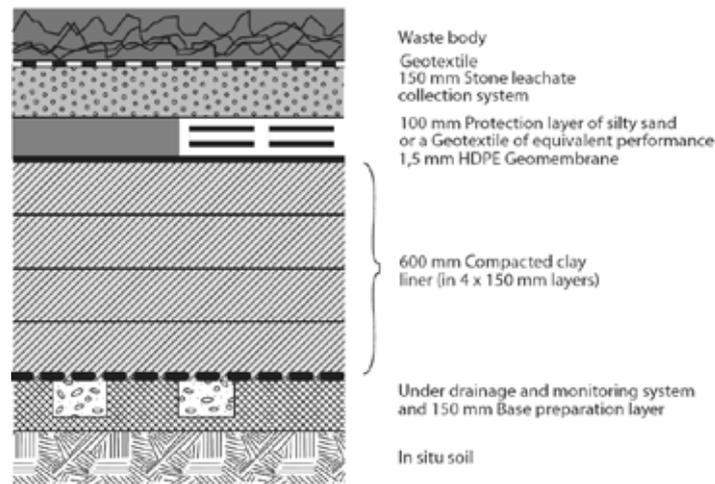


Figure 1. Class B Landfill (Government Gazette, No. 36784, 2013)

### 3. LANDFILL STABILITY

The stability of landfills has been a major concern for past and present environmental geotechnical engineers as both the short term and long term stability is vital to the performance as a containment barrier system for leachate.

According to Oweiss (1993), the stability of a landfill is controlled by the following factors:

- The properties of the supporting soil (strength and bearing characteristic).
- The strength characteristics and the weight of the refuse (density, cohesion and friction angles).
- The inclination of the slope.
- Leachate levels and movements within the landfill (affecting pore pressures, effective stress and interface friction).
- The type of cover (soil, soil-geomembrane).
- Cover resistance to erosion.

Another key element for stability calculations is the selection of design values and their possible ranges for the controlling actions. According to Dixon et al. (2003), these include:

- Slope geometry
- Material properties (example, unit weight of liner components and waste properties)
- Water pressures
- Gas pressures
- Construction plant forces
- Actions relating to the method of construction

From above, it can be seen that the inclination of the slope is a major factor that affects overall landfill stability and therefore the design and construction of legislative compliant lining systems on steep slopes are a major challenge.

#### 3.1 Methods of Stability Analysis

Currently in South Africa and internationally the limit state approach is the accepted geotechnical engineering design practice. Using this approach to analysis, there are two states in which failure can occur (Dixon et al., 2003):

Ultimate limit state where there is a complete loss of stability or function (example, slope failure), and Serviceability limit state such that the function of a structure is impaired (example, stressing of a landfill liner leading to increased permeability).

In the context of landfill lining system design (Dixon et al., 2003) states:

Stability of the lining system is the ultimate limit state; and  
Integrity of the lining system is the serviceability limit state.

Due to the difference between the ultimate limit state and the serviceability limit state, different methods of analysis for the two limit states are required.

Serviceability limit state, relates to the stresses, strains and deformations, in the system and within defined liner components, and this type of analysis requires analytical techniques such as finite difference and finite element formulations that require the use of computer programmes for analysis.

The analysis of ultimate limit state (example, slope instability) can be done by using the limit equilibrium concepts on an assumed circular arc failure plane or alternatively on a two-part wedge analysis for a finite length slope analysis as shown in Figure 2.

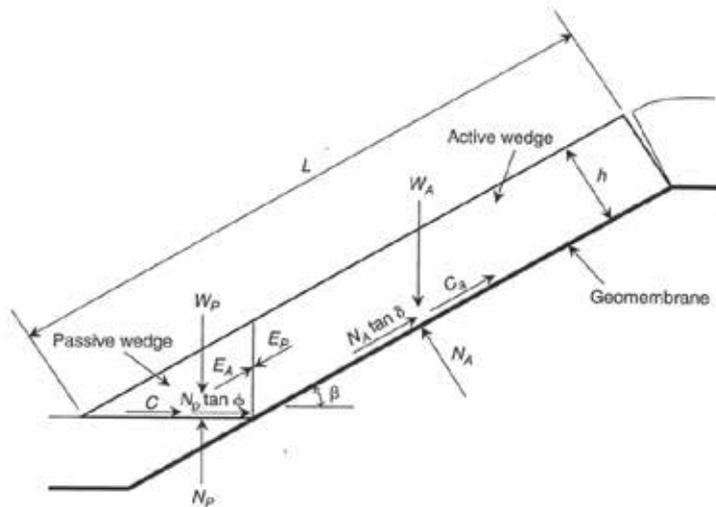


Figure 2. Limit Equilibrium forces involved in a finite length slope analysis for a uniformly thick cover soil (After Koerner and Soong, 1998)

In the above two-part wedge method, the direction of the interwedge force is assumed to be parallel to either the back slope or the front slope (U.S Army Corps of Engineers, 1960).

In the new approach of the two-part wedge method developed by Qian and Koerner in 2003 and updated by Qian and Koerner in 2004, 2005 and 2007 and by Qian in 2006 and 2008, the interwedge forces are assumed to be inclined at an unknown angle ( $w$ ) to the normal direction of the interface between the active and passive wedges and are divided into two components as shown in Figure 3.

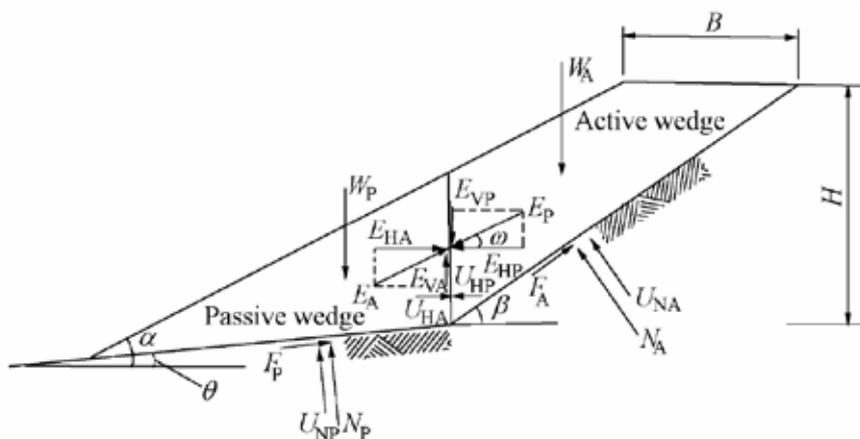


Figure 3. Forces acting on two adjacent wedges of a waste mass in a landfill cell (Qian, 2008)

For the above analyses in Figure 2 and Figure 3, the resulting factor of safety value is obtained from the following equations (Koerner, 2005 and Qian, 2008):

$$FS = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad [1]$$

Where a, b and c are represented by varying equations for both methods.

Deformations and stresses that are encountered in the serviceability limit state can be controlled in the limit equilibrium analysis by increasing the factor of safety.

The use of the above limit equilibrium tools are site specific and vital to the stability analysis of landfill lining systems.

The limit equilibrium analyses for a finite slope length was adopted for this research, as shown in Figure 2 above.

### 3.2 Factors of Safety

The definition of a Factor of Safety is the numerical expression of the degree of confidence that exists, for a given set of conditions, against a particular failure mechanism occurring (Dixon et al., 2003).

The factor of safety is based on the limit equilibrium condition and is commonly expressed as follows (Koerner, 2005)

$$FS = \frac{\text{resisting forces}}{\text{driving forces}} \quad [2]$$

$$FS = \frac{\tan \phi}{\tan \alpha} \quad [3]$$

where

$\phi$  = slope angle

$\alpha$  = friction angle between the geomembrane and its cover soil

The debate on what appropriate factors of safety for all considerations has been an endless one. Various international Directives and a commonly accepted value for the factor of safety in geotechnical engineering slope stability analysis is  $FS \geq 1.5$  for most conditions and is deemed acceptable (Thiel).

The DWAF Minimum Requirements for Waste Disposal to Landfill specifies a factor of safety of at least 1.5 for the slipping of the geomembrane liner on its underlying compacted soil layer.

The selection of an appropriate factor of safety that is required by a specific design, must also reflect the issues related to the consequences of failure namely, the risks to the environment and/or persons and the ease and cost of remedial actions.

As the commonly accepted value for the factor of safety in slope stability analysis is  $FS \geq 1.5$ , a factor of safety of 1.5 was adopted for this research.

### 3.3 Test Methods

The material properties of the various lining components used in a lining system and their interface shear are critically important for the proper design of geomembrane lined side slopes of landfill.

The testing of material properties is currently based on the newly promulgated SANS standards and international standards.

The test method used to determine the interface shear is a test adopted from the geotechnical engineering direct shear test for determining soil-to-soil friction. For the purpose of this research, a large scale 180mm outside diameter ring shear was used. The test method used to carry out the testing was adapted from ASTM D6467 – 13, The Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils. The ring shear apparatus that was used is shown in Figure 4, Figure 5 and Figure 6 below:



Figure 4. Ring Shear Apparatus.



Figure 5. Close-up of ring shear apparatus.



Figure 6. Geosynthetics after a ring shear test.

General testing procedures involved:

- A ring shear device of 180mm outside diameter and 25mm sample width
- The rate of displacement was set to 1mm/min before the tests commenced. Displacement indicators were used to check for internal movement in the GCL
- The geosynthetic materials were secured using adhesive
- Tests were performed at vertical normal stresses of 50, 100, 200 and 400 kPa. The vertical stresses were controlled using weights and lever arms
- The geosynthetic materials were hydrated and submerged during the duration of the tests
- Shearing loads were measured using two load cells mounted symmetrically about the central axis. The shear load was taken to be the sum of two load cell readings. The calibration of the load cells was checked before the tests commenced.

The above test methods result in the shear strength parameters, for the materials tested, as illustrated in Figure 7 and Figure 8 below.

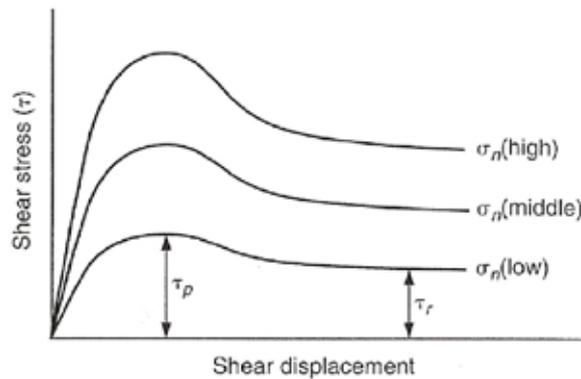


Figure 7. Direct shear test data (Koerner, 2005)

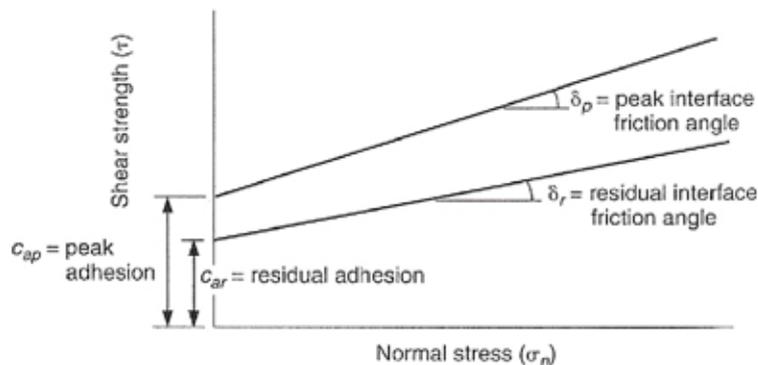


Figure 8. Mohr-Coulomb failure envelopes (Koerner, 2005)

### 3.4 Peak Shear Strength Versus Residual Shear Strength

The resultant peak shear strength and residual shear strength often leaves the designer in a dilemma. The residual shear strength is often much lower than the peak shear strength and the use of each, or a combination, results in different factors of safety. Although the use of the peak, residual or a combination of shear strength will continue to be debated, recent research recommends the following (Thiel):

- Using peak shear strengths on the landfill base, and residual shear strengths on the side slopes appears to be a successful state-of-the-practice in many situations.
- Designers should consider evaluating all facilities for stability using the residual shear strength along the geosynthetic interface that has the lowest peak strength. This would be an advisable risk-management practice for designers, even if the FS under these conditions is simply greater than unity.

### 3.5 Selection of Slope Angles

In order to determine the effects of steep slopes on the stability of a Class B landfill lining system, four (4) slopes angles were chosen for this research. The reasons for the selection of these four (4) slopes angles are explained in Table 1.

Table 1. Selection of slope angles.

Slope (V:H)	Slope Angle	Reason for selection
1 : 4	14.04°	Recommended by the new National Norms and Standards for Disposal of Waste to Landfill
1 : 3	18.43°	Recommended by the Minimum Requirements for Waste Disposal, Second Edition, DWAF 1998
1 : 2	26.57°	Adopted for this research
1 : 1	45.00°	Adopted for this research

### 3.6 Factors not included in this research

The following factors have not been considered in the above analyses and/or in this research:

- a) The effects of thermal increases on the characteristics of geosynthetics.
- b) The effects of leachate head on the factors of safety.
- c) The effects of using the methods of coextrusion, impingement or lamination for the texturing of the HDPE geomembrane.
- d) Slopes steeper than 1 in 1.
- e) The effects of Seismic forces.
- f) A cost analyses between the use of mineral lining system components and/or geosynthetic lining system components.

## 4. RESULTS AND DISCUSSIONS

From the ring shear tests carried out, the peak and residual interface friction angles and their corresponding peak and residual adhesion values are given in Table 2.

Table 2. Friction angles and cohesion values from ring shear tests carried out.

HDPE Geomembrane		Peak Friction Angle ( $\phi$ ) (Degrees)	Peak Cohesion (c) (kPa)	Residual Friction Angle ( $\phi$ ) (Degrees)	Residual Cohesion (c) (kPa)
Makro spike vs	Protection geotextile	23.17	32.26	10.88	18.43
Micro spike vs	Protection geotextile	20.92	16.59	8.42	12.66
Smooth vs	Protection geotextile	18.68	0.00	10.70	0.00
HDPE Geomembrane					
Makro spike vs	GCL	31.40	28.56	13.59	20.13
Micro spike vs	GCL	29.64	25.59	12.67	18.39
Smooth vs	GCL	18.20	0.00	7.19	0.00

Additional friction angles and cohesion values considered for this research are given in Table 3.



4.1 Configuration No. 1

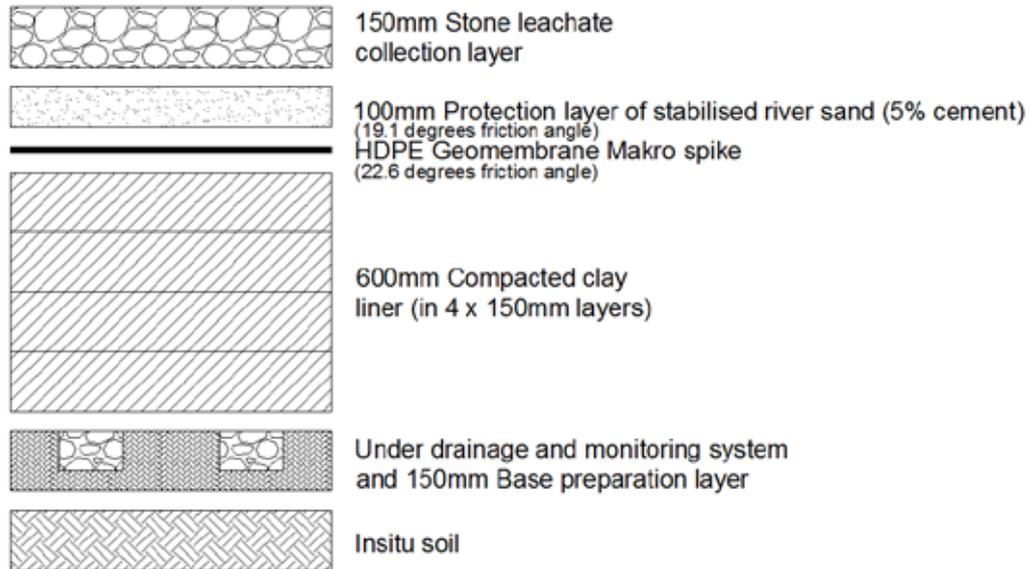


Figure 9. Configuration No. 1

The factors of safety for Configuration No. 1 are shown in Table 4 and are graphically represented in Figure 10.

Table 4. Configuration No. 1 factors of safety.

Configuration No. 1 Critical Interface: HDPE Geomembrane Makro Spike vs 100mm Protection layer of stabilised sand (5% cement)				
Factor of Safety	Slope			
	1:4	1:3	1:2	1:1
Uniform Cover Soil and Stone Layer Thickness	5.91	4.52	3.16	1.93
Uniform Cover Soil Thickness and Stone Layer Thickness with Equipment Loads	4.61	3.32	2.09	1.07

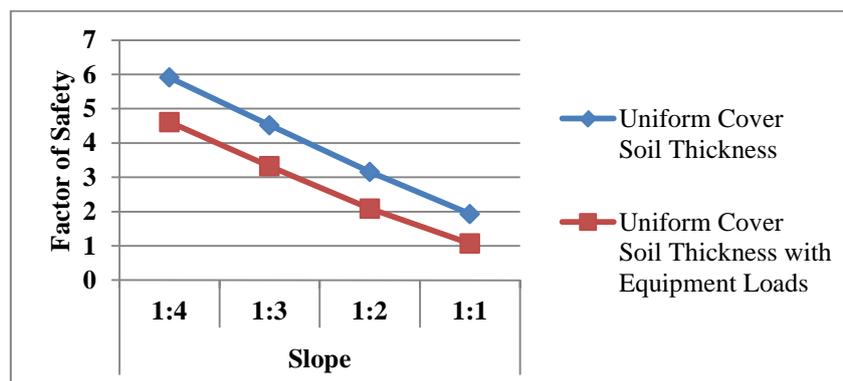


Figure 10. Graphical presentation of Configuration No. 1 factors of safety.

### 4.2 Configuration No. 2

From the materials and geosynthetics tested, many combinations were available for Configurations No. 2. The combination that was selected was based on industry norm where a single sided textured HDPE geomembrane is used, with the textured surface in contact with a GCL and the smooth surface in contact with either a mineral protection layer or a geosynthetic protection layer. The geosynthetic protection layer option was chosen for this research configuration since the friction angle was less than the friction angle against the stabilised sand layer that was tested. Configurations No. 2 is illustrated in Figure 11.

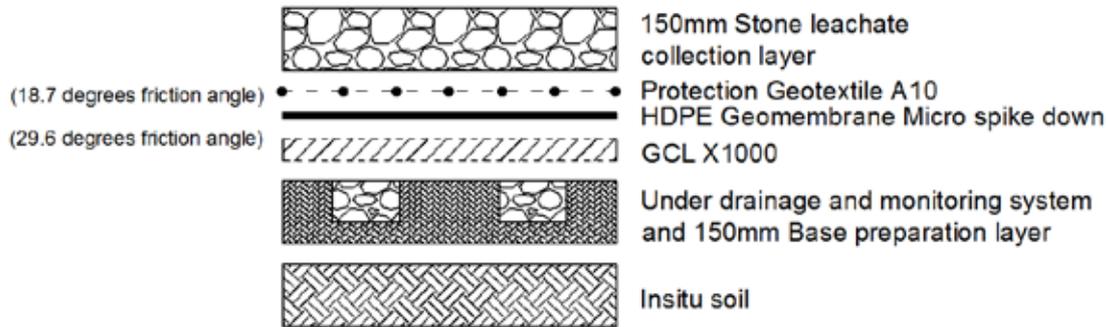


Figure 11. Configuration No. 2

Since Configuration No. 2 includes a GCL, the Hydraulic issues, Physical/Mechanical issues and Construction issues are highlighted and must be checked.

For the GCL used, the peak friction angle is 34.6° and the adhesion is 99kPa. The stability calculations, when using the GCL, assumes that the configurations do not fail due to internal shear of the GCL and must be checked.

The factors of safety for Configuration No. 2 are shown in Table 5 and are graphically represented in Figure 12.

The use of the HDPE geomembrane single sided texture with the smooth surface in contact with the protection geotextile resulted in all factors of safety < 1.5. It was therefore necessary to use veneer reinforcement. The stability calculations were therefore extended to include for veneer reinforcement for Configuration No. 2. Various strengths of veneer reinforcement were assessed and the strengths of the veneer reinforcement required to achieve factors of safety <sup>3</sup> 1.5 are also shown in Table 5.

Table 5. Configuration No. 2 factors of safety.

Configuration No. 2				
<u>Critical Interface:</u> HDPE Geomembrane Smooth Upper vs Protection Geotextile A10				
Factor of Safety	Slope			
	1:4	1:3	1:2	1:1
Uniform Stone Layer Thickness	1.39	1.05	0.72	0.87
Uniform Stone Layer Thickness with Equipment Loads	1.38	1.03	0.70	0.59
Uniform Stone Layer Thickness with Veneer Reinforcement (Rock Grid PC strength required)	1.72 (50/50)	1.68 (100/100)	3.30 (200/200)	1.75 (200/200)

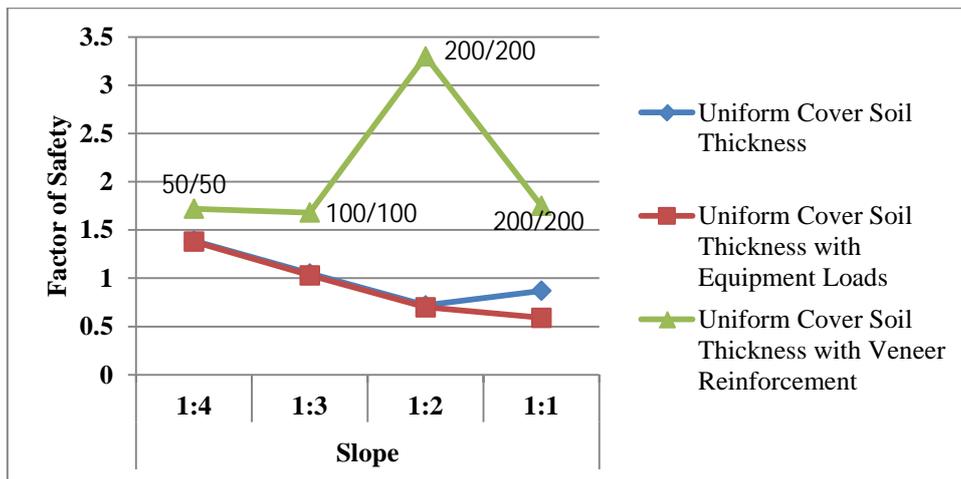


Figure 12. Graphical presentation of Configuration No. 2 factors of safety.

4.3 Configuration No. 3

The selection of the lining system components for the final configuration, Configuration No. 3, was based on using the highest friction angles attained from the geosynthetics that were tested, whilst still ensuring that the friction angle below the HDPE geomembrane was greater than the friction angle above the HDPE geomembrane and the internal shear of the GCL was greater than the highest friction angles used. Configuration No. 3 is illustrated in Figure 13.

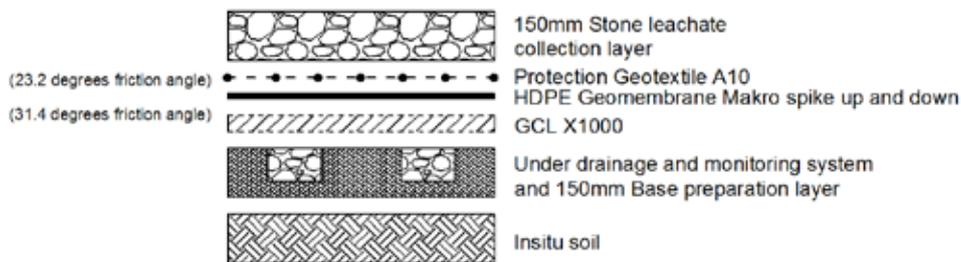


Figure 13. Configuration No. 3

The factors of safety for Configuration No. 3 are shown in Table 6 and are graphically represented in Figure 14.

Table 6. Configuration No. 3 factors of safety.

Configuration No. 3				
Critical Interface: HDPE Geomembrane Makro Spike Upper vs Protection Geotextile A10				
Factor of Safety	Slope			
	1:4	1:3	1:2	1:1
Uniform Stone Layer Thickness	40.30	30.91	21.82	13.74
Uniform Stone Layer Thickness with Equipment Loads	25.43	17.71	10.51	5.23

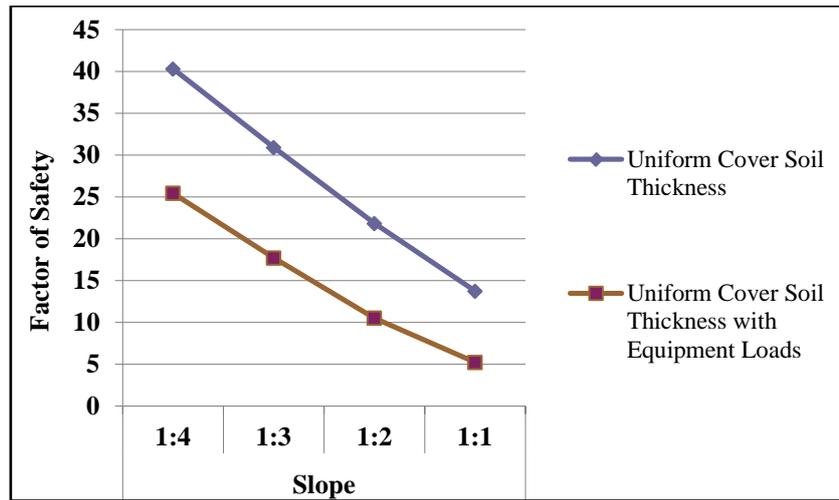


Figure 14. Graphical presentation of Configuration No. 3 factors of safety.

5. SUMMARY OF RESULTS

A summary of the various lining systems analysed with their corresponding factors of safety is shown in Table 7. The factors of safety below 1.5 are highlighted with red, the lining system components with factors of safety higher than 1.5 but have construction limitations are highlighted in green and the factors of safety above 1.5 are highlighted in yellow. The factors of safety in Table 7:

- i) the weakest interface
- ii) the various slopes
- iii) the worst case scenario which includes equipment loads

Table 7. Summary of factors of safety for analysed lining systems.

Lining System Name	Slope				Comments
	1:4	1:3	1:2	1:1	
Configuration No. 1 (Figure 9)	4.61	3.32	2.09	1.07	Based on a Class B landfill
Configuration No. 2 (Figure 11) without veneer reinforcement	1.38	1.03	0.70	0.59	Using geosynthetics with mono textured HDPE geomembrane
Configuration No. 2 (Figure 11) with varying veneer reinforcement strengths (tensile strength)	1.72 (50/50)	1.68 (100/100)	3.0 (200/200)	1.75 (200/200)	Using geosynthetics with mono textured HDPE geomembrane and veneer reinforcement
Configuration No. 3 (Figure 13)	25.43	17.71	10.51	5.23	Using geosynthetics with double sided textured HDPE geomembrane

## 6. CONCLUSIONS

From the results of Configuration No. 1 and from the materials and geosynthetics tested and used for this dissertation, it can be seen that the lining systems that are prescribed by the National Norms and Standards for Disposal of Waste to Landfill in South Africa will not be suitable on slopes steeper than 1 in 3 due to construction limitations and stability, unless geosynthetics of equal performance are considered.

Even though equivalent geosynthetic materials may be used on steeper slopes, the equivalency must be proven and the design-by-function properties of the geosynthetics must be considered.

The use of geosynthetics on gentle slopes as well as on steep slopes does not necessarily mean that the lining system stability and integrity will be achieved and must be analysed thoroughly with the stability assessment tools available. The geosynthetics used for Configuration No. 2 was based on a mono textured HDPE geomembrane liner inducing a greater friction angle below the liner, which is required, with the smooth surface of the liner in contact with a protection geotextile. Configuration No. 2 still has factors of safety below 1.5 on all the slopes i.e. 1 in 4, 1 in 3, 1 in 2 and 1 in 1, although geosynthetics were used. It is however, possible to increase these factors of safety with the use of other geosynthetics in the form of veneer reinforcement, as can be seen in the research.

The selection of the correct equivalent geosynthetic materials is a vital part of achieving acceptable factors of safety for stability on steep slopes. Configuration No. 3 consists of a double sided textured HDPE geomembrane liner and the factors of safety on all the slopes are well above 1.5.

The trending of the factors of safety for the various lining system configurations, tested for this dissertation, clearly shows a relationship between the slope angle and the factor of safety. The relationship appears to be exponential where the factor of safety exponentially decreases as the slope angle increases.

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