Slope Stability Analyses Of A Class-A Landfill Waste Body To Be Constructed On A Cliff Edge In KwaZulu-Natal

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Abstract

A new landfill cell was designed to be situated on the side of a significantly steep cliff-edge, giving rise to stability concerns of the waste landform. Stability analyses were carried out to assess the stability of the waste body. During the slope stability analysis for a landfill with a barrier system, accurately representing the critical shear strength interface within the barrier is crucial. This analysis incorporates these interfaces as a critical normal-shear function. The landfill design utilizes two distinct barrier systems: one for the basin area and another for the steeper cliff face. Both barriers are expected to exhibit differing shear strength properties over flat terrain compared to relatively steep terrain. Given the potential instability of the landform from the initial analysis, reinforcement was necessary. The design of benches, stability berms and shear keys were explored in this stability reinforcement analysis and the optimal design was selected.

Keywords: *landfill, barrier system, shear interface, stability berm, shear key*

1 Introduction

The stability of landfill waste bodies is crucial in ensuring that the surrounding environment is protected. Landfill reinforcement stability prevents the development of failure slip surfaces that may cause loss of life, damage to the surrounding environment, and substantial repair costs. The primary function of barrier systems within landfills is to contain waste and prevent hazardous substances from contaminating the surrounding environment. The shear interfaces within the barrier systems are often responsible for the formation of critical slip surfaces for landfill waste bodies as opposed to the slip surfaces within the waste body itself (Jones & Dixon, 2005). The stability of a waste body with a barrier system underneath it can be analyzed using limit equilibrium to determine if an appropriate factor of safety is attained. If the factors of safety are insufficient, then reinforcement is required that is optimal with respect to engineering and feasibility parameters.

2 Background

A landfill cell situated in the KwaZulu-Natal Province must be designed to abut against a steep cliff edge that has an average slope of 1V:1.5H. The basin of the landfill has an average slope of 1V:8H. These relatively steep configurations assist the drainage of leachate within the cell. Therefore, no significant buildup of pore pressure is expected. This is advantageous as an increase in pore water pressure within the cell may decrease the critical factor of safety (Mendoza et al., 2013). However, such steep slopes underneath the waste body promote slippage within the critical shear interface of its barrier system. Therefore, the combined effect of the barrier systems' critical shear interface and the cell geometry will determine the stability of the landfill.

The cell must be lined with a Class-A barrier system because the type of waste that the landfill is intended to contain is considered to have a high hazard rating, according to the *Minimum Requirements for Waste Disposal by Landfill* (DWAF, 1998). Due to the terrain on which the landfill is to be constructed, two barrier systems must be employed: Type 1 and Type 2 barrier systems as defined below.

2.1 Barrier System Type 1

This barrier system, illustrated in Figure 1, is a Class-A double composite barrier system that will be installed on the basin of the cell. Although the basin does not have a particularly shallow slope, the materials used in the layerworks of Barrier System Type 1 can be practically installed.

2.2 Barrier System Type 2

This barrier system, illustrated in Figure 2, will be installed on the face of the steep cliff edge between the natural ground and the waste body. This is the portion of the cell where it must abut against the cliff edge. The justification for this barrier system is that Barrier System Type 1 cannot practically be installed at the significantly steep slopes observed at the cliff edge. It is imperative that Barrier System Type 2 is incrementally installed in lifts as the waste body of the cell progresses up the cliff-edge. Moreover, the steep configuration of Barrier System Type 2 promotes continuous drainage and will rapidly direct leachate into the basin of the cell. This prevents any buildup of porewater pressure at the cliff edge and only one HDPE geomembrane, instead of a double composite lining system, is required.

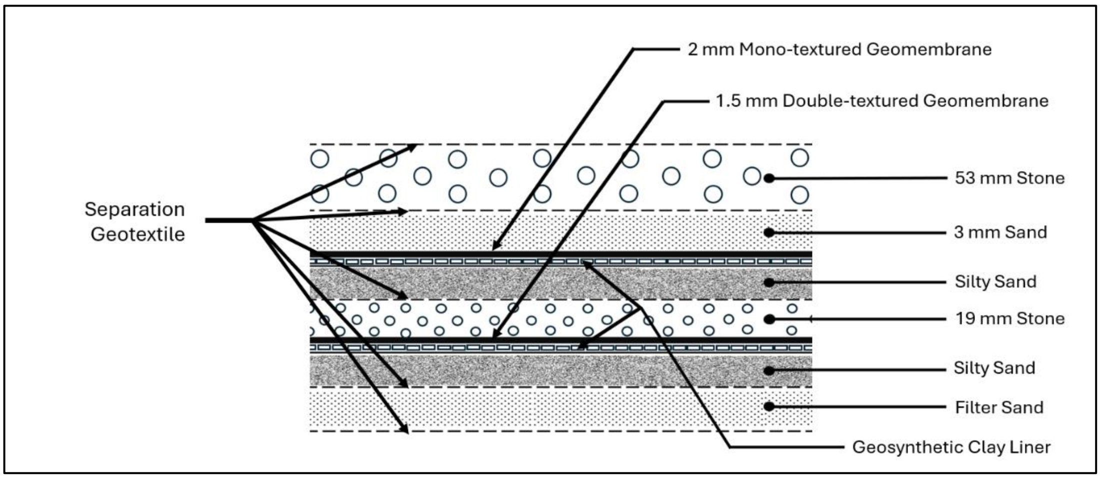

Figure 1. Barrier System Type 1

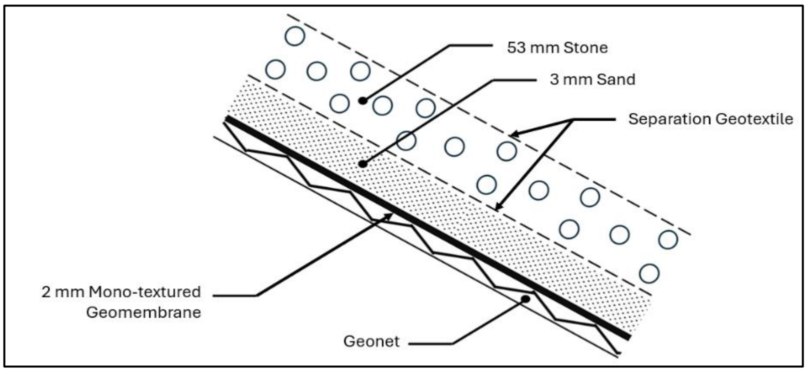

Figure 2. Barrier System Type 2

3 Slope Stability Analysis

Stability analyses were carried out using GeoStudio Slope/W (2021) based on a circular mode of failure and method of slices according to Morgenstern & Price (1965). The material properties used in the analyses are depicted in Table 1 below. The properties of the waste body were assigned to that of the *Minimum Requirements for Waste Disposal by Landfill* (DWAF, 1998). However, changes to the unit weight and friction angle are justified by the waste properties ascertained by that of existing cells onsite. The waste properties in Table 1 are still similar to the design properties of waste recommended by Dixon and Jones (2005). Residual granite fill material will be used for the construction of the stability berm and starter walls. The in-situ soil underlying the waste body is modelled to be that of impenetrable material or “bedrock”.

Table 1. Material Properties

Material	Unit weight (kN/m^3)	Cohesion, c’ (kPa)	Friction angle, Φ’ (°)
Waste	12.0	25.0	18.0
Residual Granite	19.5	5.0	24.0

3.1 Critical interface shear strength properties

Both barrier systems are expected to exhibit differing shear strength properties over flat terrain compared to relatively steep terrain due to strain softening (Reddy & Basha, 2012). According to Stark and Poeppel (1994), peak shear resistance will mobilize along the basin (flat terrain) and large-displacement shear resistance will mobilize along the side slopes (steep terrain). Therefore, the peak as well as the large-displacement failure envelope were modelled into the slope stability analyses for both Barrier System Type 1 and Barrier System Type 2. Figure 4 illustrates that the GCL (internal) failure envelope has the lowest residual shear strength. However, the residual critical failure envelope to be used in the model will be the interface that corresponds to the peak critical failure envelope (Stark & Choi, 2004), illustrated in Figure 3. All shear strength failure envelopes in the analyses were created by using test data compiled from previous projects with similar layerworks.

The critical shear interface for both peak and residual normal-shear failure envelopes of Barrier System Type 1 and Barrier System Type 2 is the protection sand and the smooth HDPE geomembrane. This confirms that the critical shear interface must be above the primary liner so that the rest of the barrier system below is still functional (Thiel, 2001).

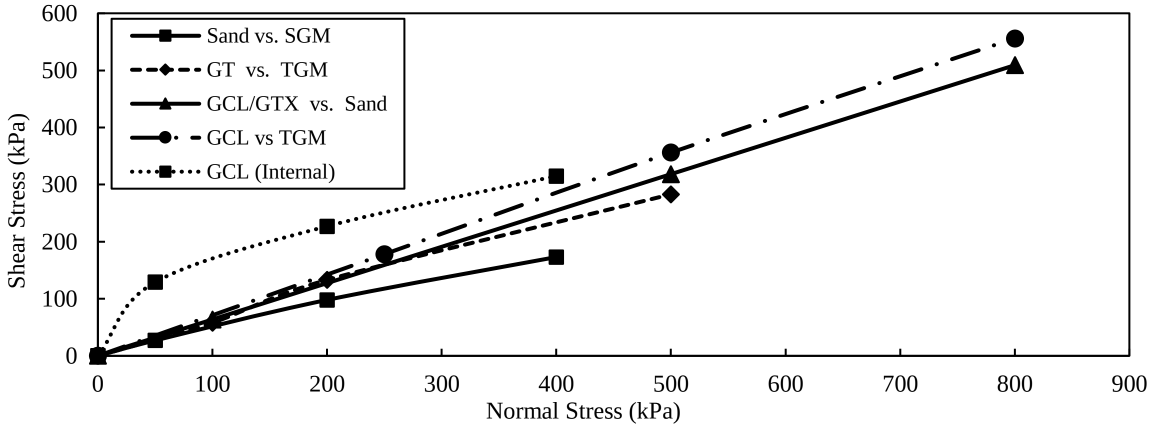

Figure 3. Failure envelope for Peak normal-shear function

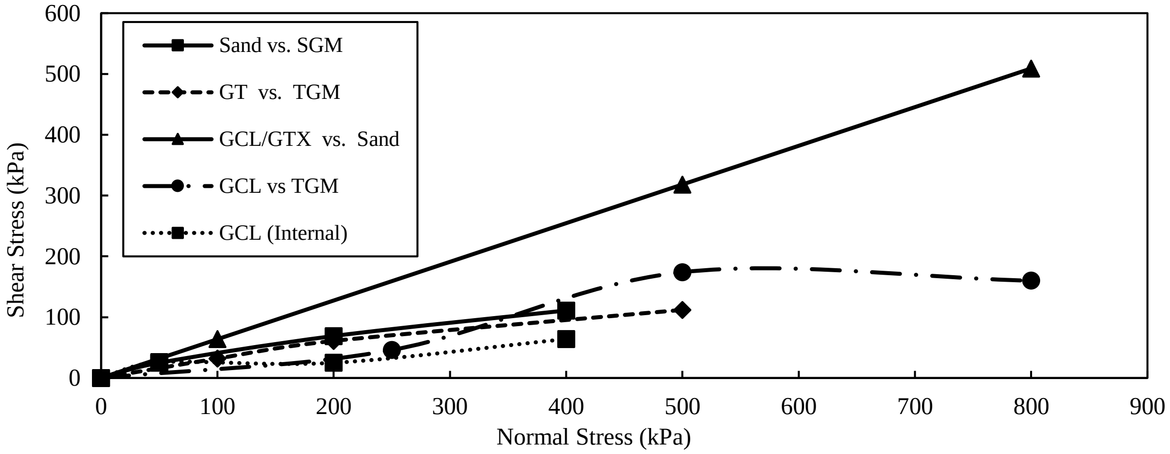

Figure 4. Failure envelope for Residual normal-shear function

4 Reinforcement design methodology

A typical profile geometry was taken to represent the stability of the cell. This profile geometry was then used to design the reinforcement required for the cell. The reinforcements should elevate the factor of safety of the profile to 1.5. At this factor of safety, the waste body can be expected to remain stable even if the actual material properties deviate from the assumed values (Thiel, 2001). Three different reinforcements were explored in the design of the cell and are listed below:

- Cliff benches
- Stability berm
- Shear key

5 Results

The profile geometry in Figure 5 below illustrates the critical slip surface through the cell. The height of the cliff edge is 80 m relative to the basin. A starter wall constructed from residual granite buttresses the waste body. Figure 5 illustrates that the slip surface occurs almost entirely underneath the waste body and through its 1.348 s also reported by Dixon & Jones (2005), resulting in an insufficient factor of safety.

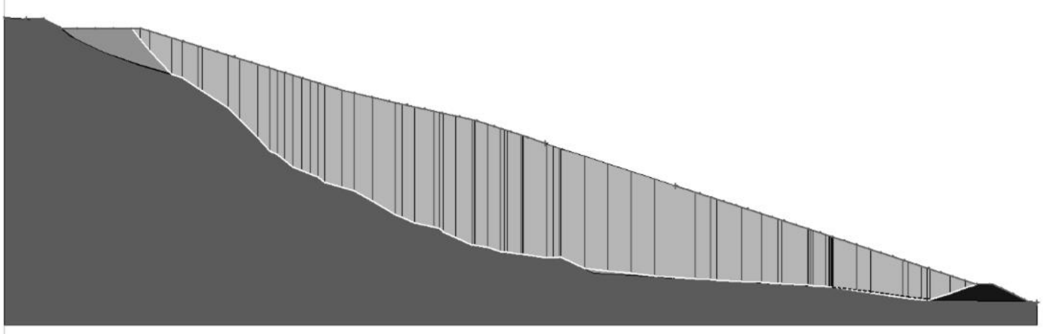

Figure 5. Critical slip surface for typical profile geometry

5.1 Reinforcement using cliff benches

The entire steep slope cliff edge portion is modelled using the residual shear interface strength properties of Barrier System Type 2. This is because no portion of the cliff-edge is flat. If the face of the cliff is slightly reshaped by cutting out 3-metre benches at approximately 10-metre vertical lifts, this will create portions on the cliff edge that are flat. This allows peak shear strength parameters to be assigned to these 3m-wide crests benches.

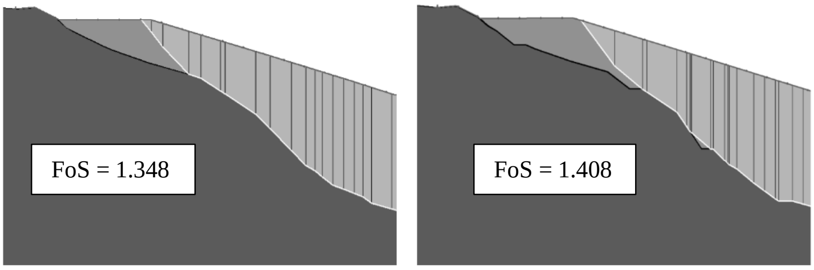

Figure 6. Effect of the factor of safety and slip surface before (left) and after (right) the reinforcement using cliff benches

5.2 Reinforcement using a stability berm

At the basin of the cell, the critical slip surface's factor of safety in Figure 5 can be increased by constructing a stability berm. This stability berm must be placed in the approximate middle of the basin. If the basin is placed too close to the starter wall, then the energy dissipating function of the berm is diminished (De Stefano et al.,2016). Its position also splits the landfill cell into appropriate phases regarding construction. Stability berms are low-cost, simple design solutions (Jiang et al., 2020) however, the disadvantage of stability berms is that they consume airspace. Therefore, the optimal stability berm was designed by obtaining the smallest stability berm that increases the factor of safety of the profile to 1.5. This was carried out by running 6 iterations of a stability berm design analysis by varying height and crest widths, while maintaining 1V:2H side slopes. The barrier system was modelled to pass over the stability berm as opposed to underneath the berm. This configuration prevents potential slip surfaces from occurring underneath the stability berm which undermines its stabilizing effect.

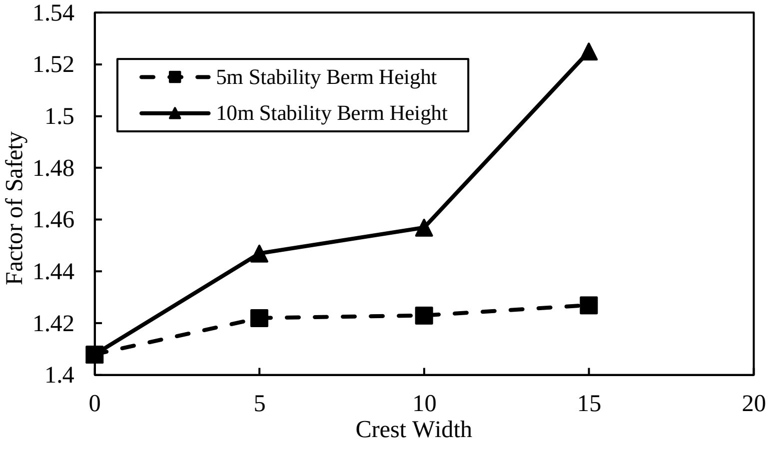

Figure 7. Factors of safety with changing cr th dimensions

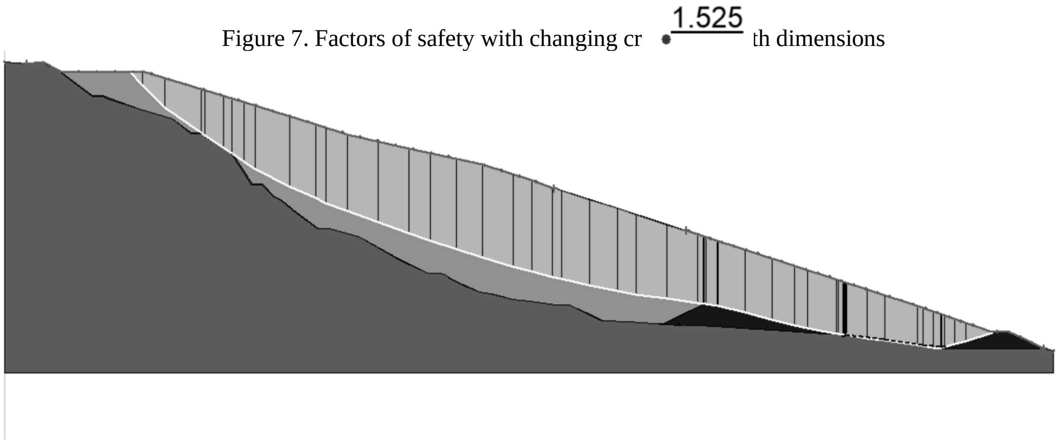

Figure 8. Factor of safety achieved with optimal stability berm

5.3 Reinforcement using a shear key

A shear key can be excavated at the toe of the inner slope of the starter wall. This key may increase the profile's factor of safety because it has the potential to divert the failure slip surface away from the barrier system and into the waste body, over the portion where the key resides. This "locks" the waste body and increases the factor of safety. Additionally, the location of the shear key will also increase the buttressing effect of the starter walls since the excavation of the shear key will create a longer inner starter wall embankment slope length. For the design analysis, where the results are illustrated in Figure 9, the shear key's width was constant, and its depth was increased in increments of 1 m until a depth of 6 m was achieved.

Figure 9. Critical slip surfaces for shear keys of 2 m (left), 4 m (middle), and 6 m (right) depths.

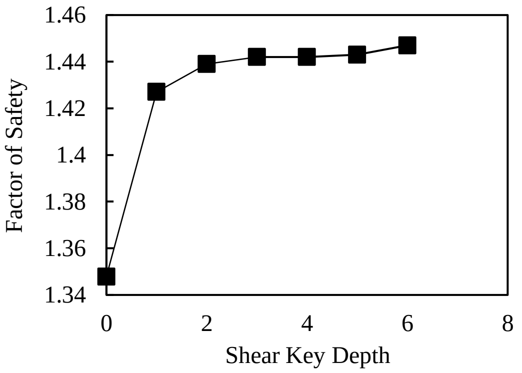

Figure 10. Change in factor of safety with changing shear key depth

6 Discussion of results

6.1 Cliff benches

The cliff benches modelled into the profile increased the factor of safety from 1.348 to 1.408. This is for two reasons. Firstly, the benches on the cliff-edge create an undulating surface on the face of the cliff edge. This allows for the dissipation of energy as the waste mass slips down the cliff-edge. Secondly, the crests of the benches are assigned to have peak shear resistive properties. This allows for the critical slip surface to pass through the waste instead of the barrier system for two of the benches as observed in Figure 6. Increasing the number of benches on the slope as well as the width of the bench crests will further increase the factor of safety. However, excavating further into the cliff edge would substantially increase the cost of the project.

6.2 Stability Berm

Figure 7 illustrates that increasing the height and width of the starter wall increases the factor of safety. However, increasing the height of the stability berm has a more pronounced effect on improving the factor of safety compared to increasing its width. The stability berm with a crest of 15 m and a height of 10 m was selected as the optimal design, resulting in a factor of safety of 1.525, illustrated on Figure 8. The critical slip surface for the optimal design scenario does not slip underneath the berm and along the basin's barrier system. Instead, the stability berm is observed to lift the slip surface away from the barrier system and through the stability wall, increasing the factor of safety. Shorter stability berms, regardless of their width, allow slip surfaces to occur in the waste body or barrier system above their crests.

6.3 Shear key

The results of Figure 10 illustrate that even relatively shallow shear keys (approximately 1 m) will significantly increase the factor of safety from 1.348 to 1.427 because the failure slip surface slips through the waste instead of the barrier system. However, increasing the depth of the shear key (greater than 2 m) is observed to not have any significant effect on the factor of safety. This is because the slip surface slips through the waste and shears the key which will match the same failure slip surface, regardless of the depth of the key. This is illustrated in Figure 9. In order to design shear keys that have a significant effect on the factor of safety, the width of the shear key must be increased but not necessarily its depth. This will increase the length of the plain at which the key is sheared, which will increase the factor of safety.

7 Conclusion

A landfill to contain waste of a high hazard rating was designed to be abutted against a steep cliff-edge. This gave rise to two barrier systems: Barrier System Type 1 and Barrier System Type 2. Barrier System Type 1 is a fill Class-A barrier that can only be installed on relatively flat areas. However, the Barrier System Type 2 is suitable to be installed on the steep cliff-edge. These barrier systems were assigned peak or residual shear strength properties based on the slope on which they reside.

A slope stability analysis was carried out to assess the factor of safety of the profile, which was observed to require reinforcement. Increasing the factor of safety of the profile geometry was explored by cliff benches, stability berms, and shear keys. The cliff benches used in the design increased the factor of safety significantly. Increasing the number of benches as well as their width will further increase the factor of safety. The stability berms modelled illustrate that increasing the height of the berms has a greater impact on the factor of safety compared to increasing the width of the berms. Regardless, increasing the width and/or the height of the stability berms will still increase the factor of safety, ensuring that the barrier system is installed over the stability berm and not underneath it. Regarding the design of shear keys, increasing the width of the shear key will have a greater effect on increasing the factor of safety compared to increasing the depth of the shear key only. Increasing the depth of the shear key will have no effect on the factor of safety once the critical slip surface shears the waste over a given shear key. The final design of the slope geometry incorporated the cliff benches and the optimal stability berm. The shear key was not included in the final design due to its significant influence in the cost of excavation as well as the excessively deep outlet drainage pipes that would be required.

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