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Review of the waste slope stability design of a landfill site in Gauteng

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Abstract

The objective of this paper is to review the slope stability analysis conducted during the initial design stages of a new landfill cell that is part of a landfill site expansion in Gauteng. The SLOPE/W slope stability software, from the Geostudio integrated software suite, was used to carry out the analysis. Initial trials revealed a significant waste slope instability, which, when further investigated, was attributed to the 8 m deep basin, the weak sliding interface between the smooth geomembrane and clay, the 46 m estimated waste height leaning on a small embankment on the northern side of the cell and the cell basin sloped in the direction of the driving force of the waste sliding mass. Satisfactory results and eventually slope stability was achieved through a comprehensive optimisation process which entailed modelling and running iterations of various trials of a combination of stabilising berms, geogrids and cutting back the waste slope.

Keywords: *SLOPE/W, shear strength, geosynthetic.*

1 Introduction

The stability assessment of a landfill waste disposal facility is one of the requirements by the Department of Water and Sanitation (DWS) as stated in the Minimum Requirements of Waste Disposal by Landfill (Department of Water Affairs and Forestry, 1998). This assessment entails investigating the stability of the slopes cut into natural soils against shear failure as well as the waste slopes, especially when the slopes are steep, high or both, against shear failure through the waste, the weakest interface in the liner system or the in-situ material. There are key factors that play a significant role in facilitating slope failures. These factors are site-specific and are critical to the functional stability of the landfill. They are listed as follows (Law, 2015):

- In-situ material condition: Weak shear planes may occur in the in-situ materials below the liner system and thus have to be investigated;
- Soil and geosynthetic interfaces (in the liner system): The weakest shear planes generally occur in geosynthetic/geosynthetic and soil/geosynthetic interfaces;

- Selection of critical cross sections: This involves identifying a few critical cross sections that are perpendicular to the waste slopes and will potentially yield the lowest factor of safety;
- Waste unit weight and shear strength: The selected values of these parameters will have a significant influence on any shearing through the waste;
- Phreatic surfaces: The expected leachate head in the cell must be investigated because without a functional drainage system the leachate head will build up and cause an instability of the waste body. The level of the phreatic surface in the in-situ material must also be considered;
- Operating conditions: Operation of a functional drainage system for stormwater infiltrating the waste body;
- Monitoring: Monitor landfill performance to confirm that the observed field conditions match those that were assumed in the analysis.

Selection of appropriate shear strength parameters is a key aspect of the slope stability analysis, which relies on information on waste composition, particle size, degree of degradation, and moisture content. One of the most difficult tasks for evaluating slope stability in Municipal Solid Waste (MSW) landfills include accurate determination of shear strength parameters and weight units for waste. Although significant scatter exists in these parameters due to the natural characteristics of MSW, considerable efforts have been made toward finding generic rules for these parameters.

Currently in South Africa and internationally, the limit state approach is the accepted geotechnical engineering design practice. Using this approach 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 i.e., slope failure;
- Serviceability limit state such that the function of a structure is impaired i.e., stressing of a landfill liner leading to increased permeability.

The stability analysis discussed in this paper was conducted according to the ultimate limit state.

2 Background

Due to the airspace of the current landfill nearing capacity a new cell is required for the landfill to continue operations therefore the design of the new cell is currently underway and will be constructed adjacent to the existing landfill in the northern direction as shown in Figure 1. A stability assessment was conducted as an integral part of the design process and a requirement by the DWS for the approval of the design. The final landform of the waste body used in the analysis considered not only the waste in this cell but also additional waste from an anticipated future extension of the facility.

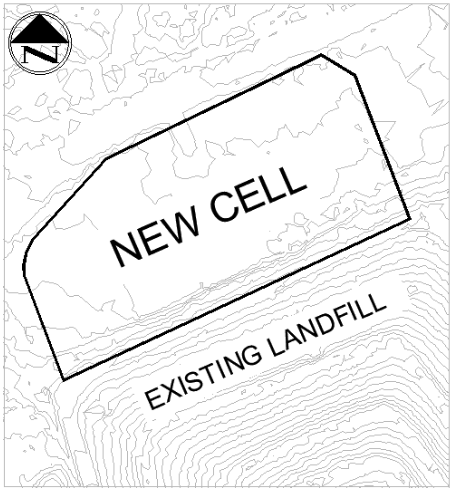

Figure 1. Plan layout

2 Slope stability evaluation

SLOPE/W from the Geostudio integrated software suite was used to perform the analysis. SLOPE/W is a specialised software program specifically suited to analysing the stability of soil and rock slopes as 2-Dimensional (2D) plane strain problems. The program allows the user to analyse problems with varying degrees of complexity which considers varying pore water pressure conditions, soil properties, geometries, external loading conditions and slip surface shapes.

2.1 Critical cross section

The geometry of the cell and the waste profile i.e., final landform was modelled on AutoCad Civil 3D. One critical cross section was identified as shown in Figures 2 & 3 (Section A-A). The critical section includes waste from the future extension. It is important to consider the additional waste because it will increase the normal force and subsequently the shearing force along the weakest plane in the waste.

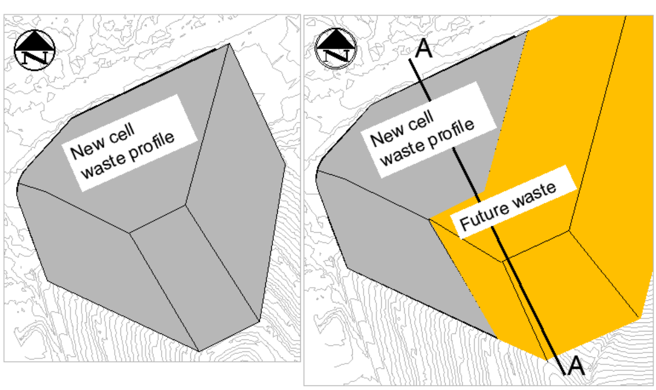

Figure 2. Critical cross section

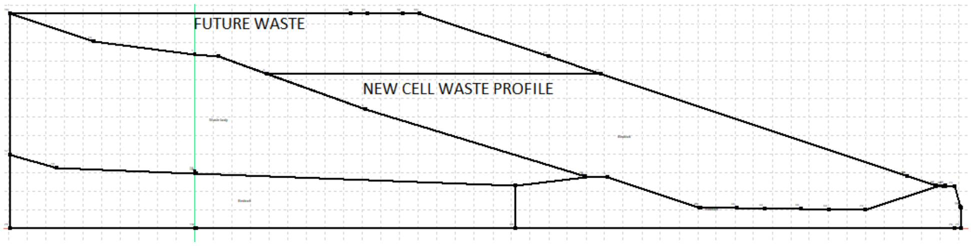

Figure 3. Longitudinal section

2.2 Material properties

The material properties used in the analysis are listed in Table 1. It is imperative to input material properties that are a good representation of the material to be used in construction. The shear strength properties used in this analysis were sourced from:

- Clay – Shear box test performed on clay from a previous project in the same site;
- Waste – Minimum Requirements for Waste Disposal by Landfill (Department of Water Affairs and Forestry, 1998) and from an article published by the Geotextiles and Geomembranes journal on the properties of municipal solid waste (Dixon et al., 2004).

Table 1. Material properties

Material	**Unit weight (kg/m^3)**	**Friction angle (kPa)**	**Cohesion (kPa)**
Clay	16.5	20	22.2
Waste (Minimum Requirements)	10	15	25

2.3 Shear strength parameters

A suitable liner system, shown in Figure 4, was designed in accordance with the National Norms and Standards for Disposal of Waste to Landfill (GN 636) and the Minimum Requirements for Waste Disposal by Landfill (Department of Water Affairs and Forestry, 1998). The liner system on the side slopes of the cell has a mono-textured geomembrane with the texturing at the bottom. Prior to commencing with the analysis, a weak shear interface was identified in the liner system. Shear tests were conducted for all the interfaces in this liner for a previous project in the same area. Peak and residual/large displacement shear envelopes were plotted from these test results, and these are displayed in Figure 5 and 6 below.

"The interface along which detrimental shear displacement may occur is the interface that exhibits the lowest peak interface shear resistance in the bottom liner system regardless of the value of the residual interface shear resistance. For example, if the interface with the lowest peak interface shear resistance exhibits the highest residual interface shear resistance, the detrimental shear displacement may still occur along this interface, but the resulting stability will be controlled by the residual interface shear resistance along this interface and not the lowest residual interface strength…" (Stark et al, 2004). In this case the weakest interface is the textured geomembrane on clay both on the basin and the side slopes. The corresponding residual interface is the same interface; however, this is not always the case. This is the interface that was used for the analysis.

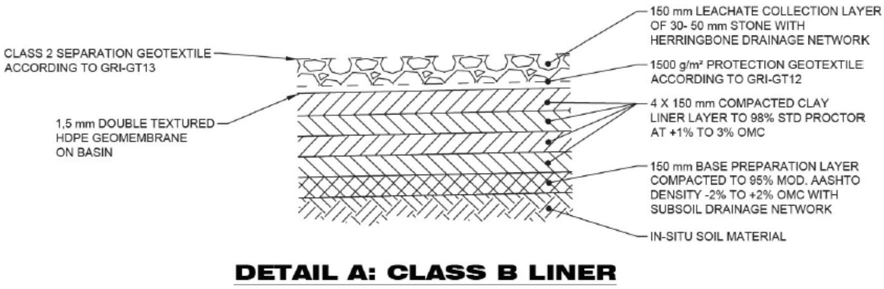

Figure 4. Liner system

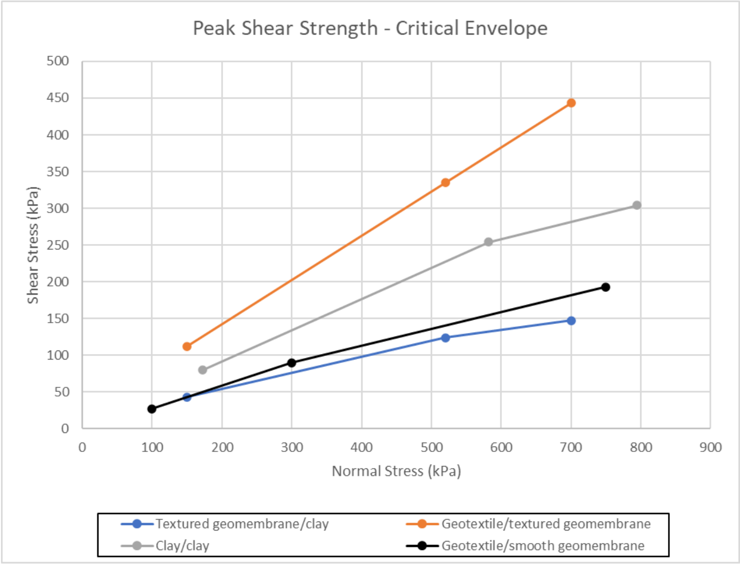

Figure 5. Peak shear strength envelopes

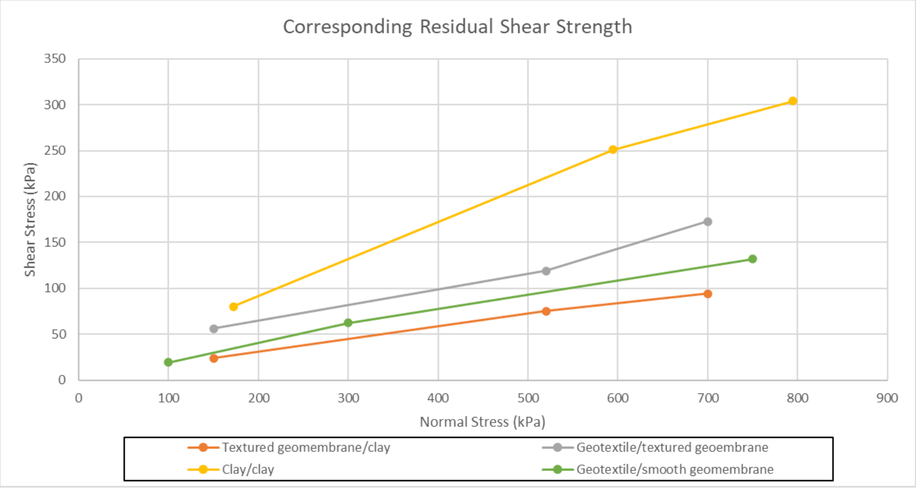

Figure 6. Residual shear strength envelopes

2.4 Phreatic surface

A piezometric line was drawn at 0.3 m above the leachate collection layer. This is because a functional drainage system will be designed, therefore a build-up of hydraulic head in the cell is not expected. Trials at 0.5 m and 1 m were performed.

3 Results

Two scenarios were analyzed for each trial (Stark et al, 2004):

- Scenario 1 – Assigning residual shear strength on the side slopes and peak shear strength properties for the basin;
- Scenario 2 – Assigning residual shear strength properties for the basin and side slopes.

The basis of evaluation of the results in correspondence to the above scenarios is a factor of safety of 1.5 and above for scenario 1 and unity for the scenario 2. The fundamental principle behind these scenarios is that on the side slopes a low shear resistance is exhibited because of the low normal force exerted and therefore a greater degree of mobilization of peak shear strengths. Scenario 2 is a conservative approach assuming a worst-case scenario of mobilization of all peak shear strengths both in the side slopes and basin.

3.1 Initial trials

Several slope failures were observed after running the initial trial with the critical failure yielding a factor of safety of 1.083. An investigation was conducted to identify the factors driving the critical slope failure. The following factors were identified:

- It is apparent from Figure 7 that there is a huge mass of waste sliding along the weakest failure plane. The vertical height of the waste up to the final landform is 46 m and this greatly influences the stability of the waste.
- Trials that involved increasing the height of the northern embankment on which the waste leans albeit not a significant increase in stability was observed. Due to drainage on the crest of the cell there was a restriction on the increase in the embankment height.
- The depth of the basin.

- The most critical element that resists the sliding mass of waste is the shear resistance of the weakest interface within the liner system. As mentioned earlier the weakest interface was identified as the textured geomembrane on clay. The shear strength properties in this interface were relatively low as shown in Table 2 below. Direct shear tests performed yielded the following for this interface:

Table 2: Shear strength parameters

	Peak (kPa)	Residual (kPa)
Friction angle	11	7.3
Cohesion	16	6

- To design and operate a gravity drain system for both the leachate and subsoil drains, the outlet of the cell was positioned such that the basin was sloping in the direction of the shear force in the critical plane which further deteriorated the instability of the waste.

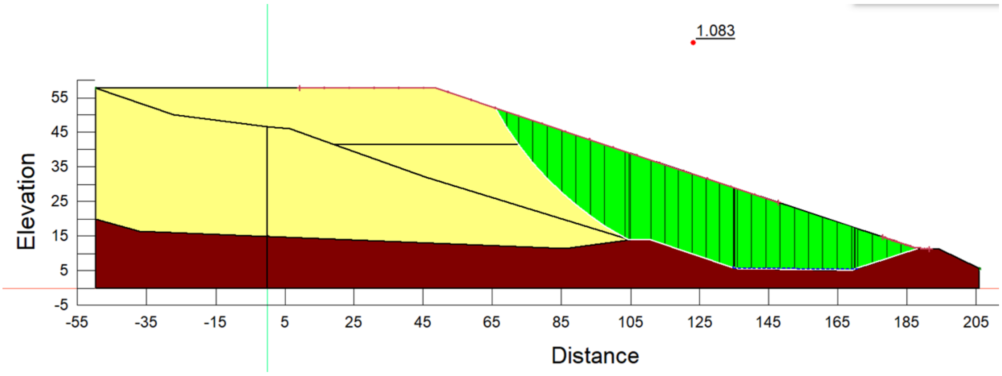

Figure 7. Initial trial

3.2 Stabilising mechanisms

Consequently, various stabilising mechanisms were considered with the purpose of achieving stability while maximising airspace capacity for the client. The following mechanisms were modelled and assessed in this order:

1. Stability berms – 2 x 1.5 m clay berms were modelled on the cell basin perpendicular to the direction of the critical slip plane.
2. Reducing basin depth – A conclusion drawn from the initial trials was that the instability is affected by the deep basin depth. The length of the side slope affects the magnitude of the active wedge in the failure surface. Multiple trials were conducted at different basin depths with a combination of stability berms.
3. Cutting back waste slope – Although not ideal, cutting back the slope of the waste was a consideration. The original slope was 1:3 but it was cut back to flatter slopes in different scenarios to as far as 1:3.9. The different scenarios analysed were in combination with the aforementioned factors.
4. Geogrid reinforcement – The last consideration was a geogrid installed on the basin and side slopes above the weakest interface to allow the shear force of the failure plane to be exerted on the geogrid before reaching the weakest interface. This process involved the use of high strength geogrids i.e., high tensile strength, that are normally used in geotechnical applications. The geogrids utilised were designed according to the BS 8006-1: 2010 and the British Board of Agrément (BBA)

HAPAS Certificate Product Sheet for high strength geogrids. It is worth noting that the geogrids were designed to fail in tension in this analysis and a design to ensure they are sufficiently anchored against pullout will have to be carried out.

A comprehensive optimisation process was performed with a combination of all the above components. A summary of all the successful scenarios is shown in Table 3.

Table 3. Summary of optimised scenarios

Basin depth	**Scenario**	**Geogrid (Grade)**	**Waste cut back (Slope)**	**Stability berm**
2m	1	-	1 in 3.6	3 berms
3m	2	-	1 in 3.6	3 berms
	3	400/40	1 in 3.3	3 berms
	4	1200/100	1 in 3.2	3 berms
4m	5	1200/100	1 in 3.2	2 berms
5m	6	1200/100	1 in 3.2	2 berms
8m (Original basin)	7	400/40	1 in 3.9	-
	8	400/40	1 in 3.7	1 berm
	9	1200/100	1 in 3.3	1 berm

3.3 Optimised model

Scenario 9 was chosen as the most optimal in terms of airspace and cost. A further optimisation was performed on this scenario to achieve more airspace for the client. The following modifications were carried out:

- A second 1200/100 was introduced in the waste through the failure surface. The optimal level of this geogrid was found to be on the crest of the left embankment. This geogrid acts as a reinforcement to carry the force of the failure surface in tension;
- A second stability berm was added in the basin;
- The above modifications allowed the waste slope to be increased to 1 in 3.1.

The modifications are shown in Figure 8 and the resulting stability analysis is shown in Figure 9.

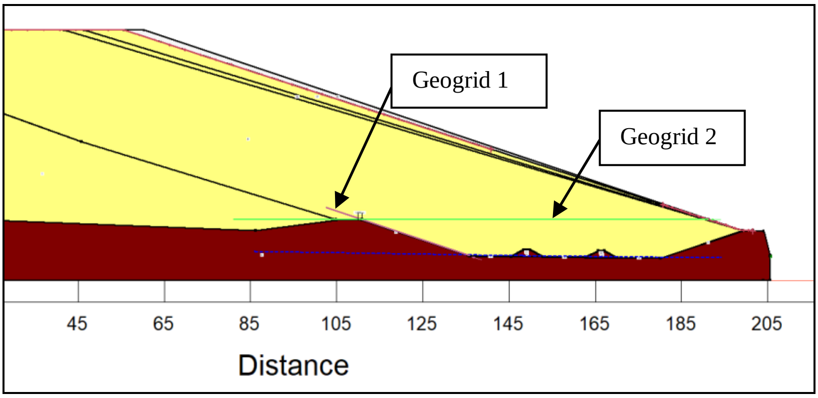

Figure 8. Optimised model

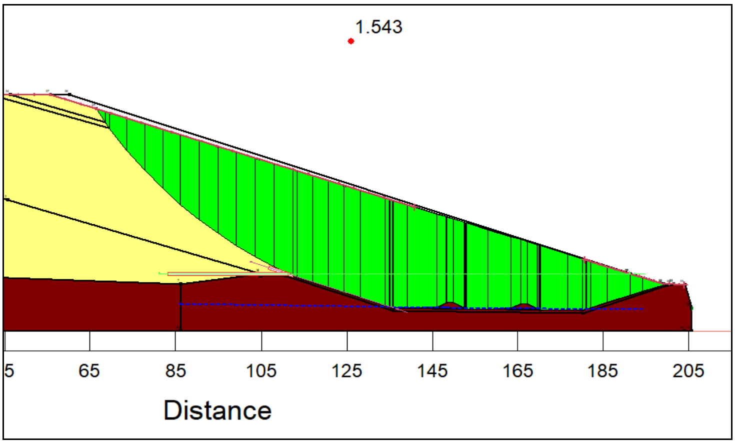

Figure 9. Optimised model (SLOPE/W output)

4 Conclusions

The following conclusions can be drawn from the stability analyses presented here:

- The cell geometry plays a major role in the stability of the waste material and should be considered carefully during the design process;
- The importance of selecting appropriate shear strength properties cannot be over emphasized;
- Stabilising mechanisms e.g., berms, geogrids etc. should be considered in cases where the required stability cannot be achieved, albeit the cost implications of these should be kept in mind;
- Cutting back the waste should as far as possible be avoided if not necessary;
- A check of the stability analysis using another method is recommended.

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