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

Simphiwe Zondo[1]

[1]Zutari, Geotechnical Department, Cape Town, South Africa

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 forms 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 weak sliding interface between the smooth geomembrane and clay, the 8 m deep basin, 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 waste sliding mass. Satisfactory results and eventually slope stability was achieved through a comprehensive optimization process which entailed modelling and running iterations of various trials of a combination of stabilizing berms, geogrids and cutting back the waste slope.

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 [1]. This assessment entails investigating the stability of soil slopes and waste slopes against shear failure. There are key factors that play a significant role in facilitating slope failure and these are listed below [2]:

- Cross sections: Sections orthogonal to the potential sliding waste mass;
- Shear strength parameters: Selection of appropriate material and interface shear strength parameters;
- Water table: Leachate levels in the waste body affect the shear strength of the waste;
- Operating conditions: Implementing a functional drainage system for stormwater infiltrating the waste body.

Obtaining appropriate shear strength parameters is critical to the outcome of a stability analysis. The shear strength of waste material depends on depends on several factors including waste composition, degradation, moisture content and particle size [3]. Thereafter, an appropriate factor of safety must be selected. The limit state approach is the accepted geotechnical engineering design practice and this entails the following in the context of a landfill site [4]:

- Ultimate limit state where there is a waste slope failure;
- Serviceability limit state where there the liner is overstrained and damaged.

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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.

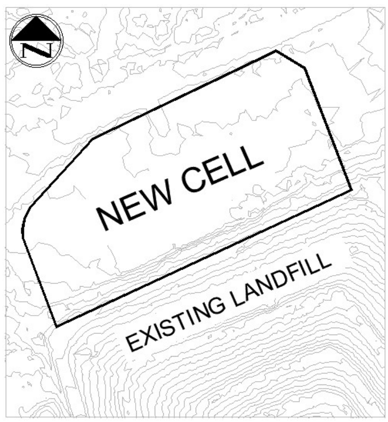

Fig. 1. Plan layout

3 Slope stability evaluation

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

3.1 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 stress and subsequently the shearing stresses along the weakest plane in the waste.

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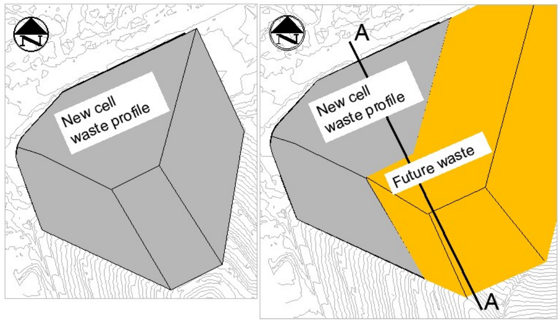

Fig. 2. Plan view with critical cross section

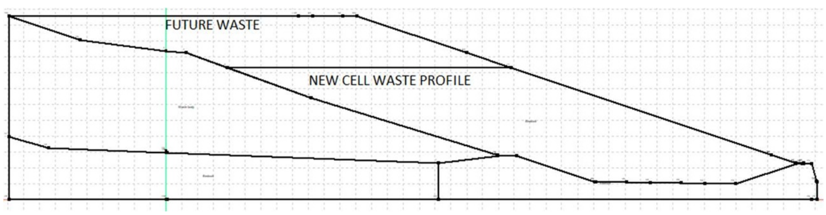

Fig. 3. Critical cross section

3.2 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 [1] and from an article published by the Geotextiles and Geomembranes journal on the properties of municipal solid waste [5].

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

3.3 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. 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

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residual/large displacement shear envelopes were plotted from these test results, and these are displayed in Figure 5 and 6 below.

Shear displacement will occur along the interface with the lowest peak shear strength and therefore will continue on that same interface until large or residual displacements are reached [6]. 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. This is the interface that was used for the analysis.

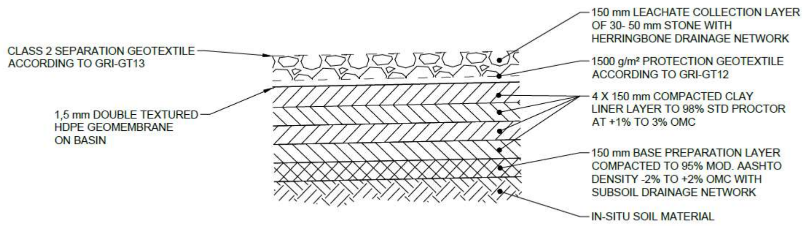

Fig. 4. Class B liner system

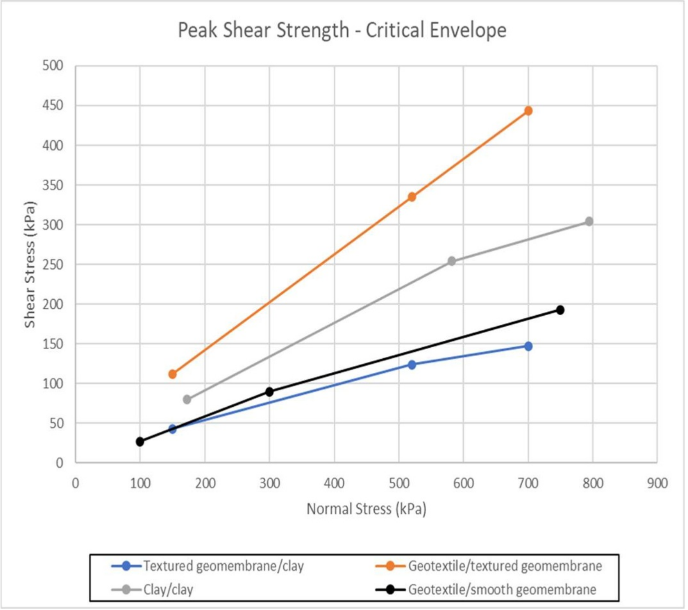

Fig. 5. Peak shear strength envelopes

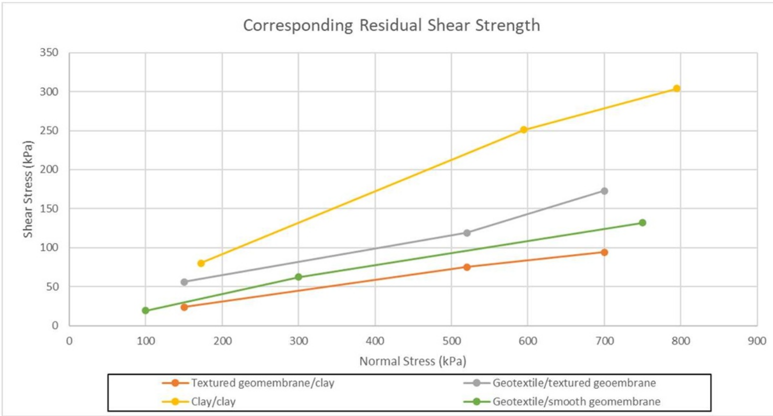

Fig. 6. Residual shear strength envelopes

3.4 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.

4 Results

Two scenarios were analyzed for each trial [6]:

- 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.

4.1 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

Parameter	**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.

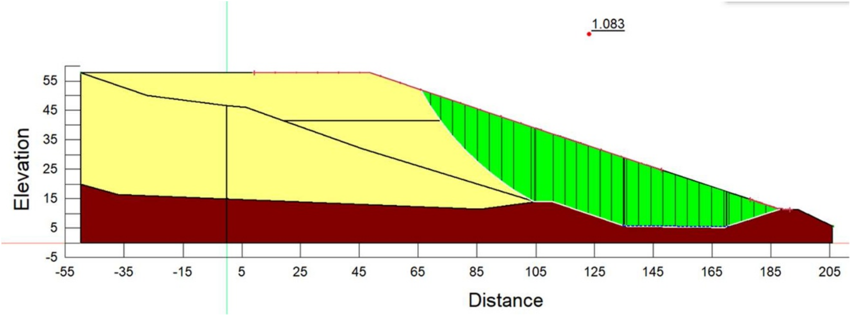

Fig. 7. Initial trial

4.2 Stabilizing mechanisms

Consequently, various stabilizing mechanisms were considered with the purpose of achieving stability while maximizing 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 analyzed 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

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normally used in geotechnical applications. 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 optimization process was performed with a combination of all the above components. A summary of all the successful scenarios is shown in Table 3. Scenario 6, albeit yielding a larger airspace, requires a large amount of fill material and thus cost significantly more. Similarly, scenarios 1 to 5 would require a lot of fill material because of the shallow basin depth and result in significant construction costs. The cut and fill is balanced for scenarios 7 to 9.

Table 3. Summary of optimized scenarios

Basin depth	Scenario	Geogrid (Grade)	Waste cut back (Slope)	Stability berm	Factor of safety	Airspace (m^3)
2m	1	-	1 in 3.6	3 berms	1,578	217 972
3m	2	-	1 in 3.6	3 berms	1,541	227 676
	3	400/40	1 in 3.3	3 berms	1,516	260 484
	4	1200/100	1 in 3.2	3 berms	1,569	272 613
4m	5	1200/100	1 in 3.2	2 berms	1,540	292 105
5m	6	1200/100	1 in 3.2	2 berms	1,533	299 254
8m	7	400/40	1 in 3.9	-	1,536	248 130
	8	400/40	1 in 3.7	1 berm	1,499	260 803
	9	1200/100	1 in 3.3	1 berm	1,506	295 638

4.3 Optimized model

Scenario 9 was chosen as the most optimal in terms of airspace and cost. Further optimizations were carried out as follows:

- 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 optimizations allowed the waste slope to be increased to 1 in 3.1.

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

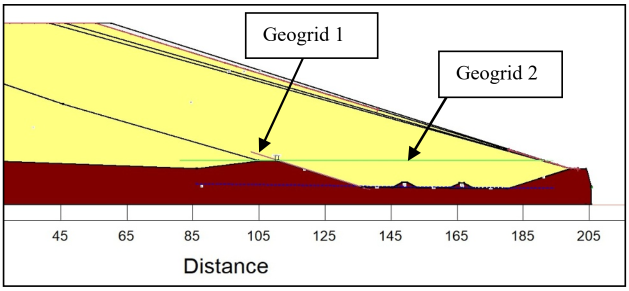

Fig. 8. Optimized model

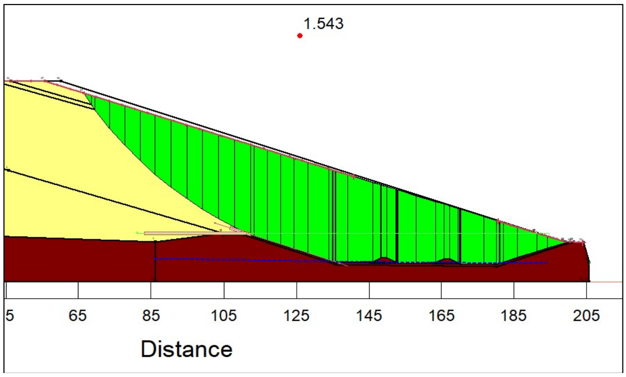

Fig. 9. Optimized model (SLOPE/W output)

5 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;
- Stabilizing 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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