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Optimisation of lined waste facility geometries

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Abstract

Stability analyses of lined waste facilities were done to investigate the effect of geometry on the stability of the facilities. Three different waste types were considered for a 15 m high facility with three benches. It was found that both the stability and the capacity of the facility can be increased by constructing the bottom bench at a slope steeper than the remainder of the facility. Consequently, the geometry with the flattest slopes is not necessarily the safest nor the most economical design.

Keywords: *slope stability analysis, geosynthetic interface, optimisation, waste storage facility*

1 Introduction

The stability of a slope is the determined by two components: 1) the forces or moments driving failure and 2) those resisting failure. By increasing the forces resisting failure the stability of the slope can be improved. These forces can be increased by either improving the shear strength of the waste or by increasing the mass of waste resisting failure.

In lined waste facilities the critical slip surface typically extends down to the geosynthetic interface as its shear resistance is weaker than the remainder of the waste body. In Figure 1 such a failure of a lined waste facility is illustrated. The failing waste body can be divided into two components: 1) the active block driving failure and 2) the passive block resisting failure. In this paper it will be investigated whether the stability of the facility can be improved by steepening the slope and thus increasing the weight of the passive block.

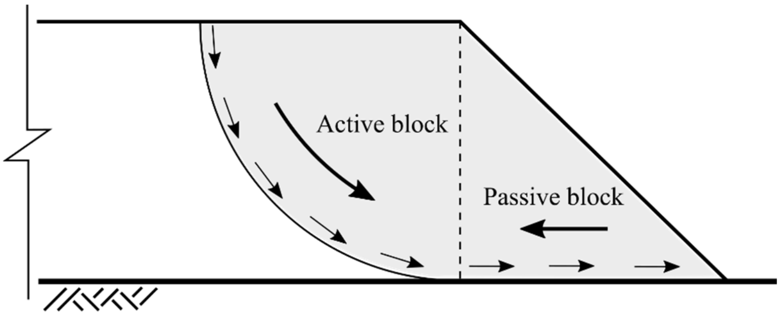

Figure 1. Idealised failure of a lined waste facility

2 Methodology

A series of stability analyses were done to determine the optimal geometry for the stability of a lined waste facility. The idealised facility consisted of three benches, each five meters high with a three meter step. The slope of each of the three benches was either modelled as 1:3 (A) or 1:2 (B) with all possible combinations of slopes considered. In addition to the bench slopes, the depth of the basin was also varied between, flat, 2.5 m deep and 5 m deep.

One of the scenarios analysed, a facility with a 1:2, 1:3 and 1:2 slope and a 2.5 m deep basin (B-A-A-2.5), is illustrated in Figure 2. Other possible geometries are shaded in grey. The flattest geometry, with all three slopes at 1:3, has the lowest storage capacity and was used as basis of comparison for the analyses.

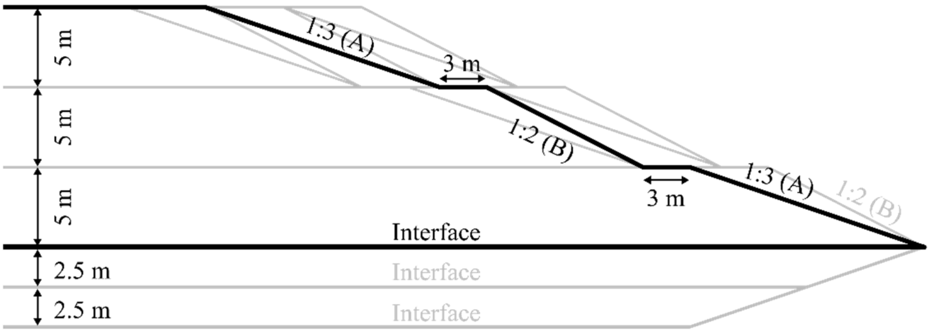

Figure 2. Typical geometries analysed for stability

The geosynthetic interface was modelled as a 50 mm thick layer with an impenetrable layer below. This forced deep seated failures to run along the liner, rather than through it. Analyses without any liner system was also done for one of the waste types for the purpose of comparison.

The stability analyses were done using GeoStudio's SLOPE/W package. The grid-and-radius method was used to search for the critical slip surface while the Morgenstern-Price method (Morgenstern & Price, 1965) was used to evaluate the factor of safety (F.o.S.) of each configuration.

In principle the F.o.S. is the ratio between the forces (or moments) driving failure to the forces resisting failure. The greater the F.o.S., the more stable the facility. A F.o.S. of less than one indicates that the forces (or moments) driving failure is greater than those resisting failure and that failure is possible.

For most lined landfills, classes A, B and C (DEA, 2013), the weakest interface is typically designed to be above the liner to prevent damage to the liner during a slope failure. In order to achieve this a protection geotextile can be placed on top of a smooth primary geomembrane. The peak and residual strength of this configuration is $\phi = 11°$, $c' = 0$ kPa and $\phi = 9°$, $c' = 0$ kPA respectively (Koerner & Narejo, 200). For this series of analyses only a peak interface strength of $\phi = 12°$, $c' = 0$ kPa was considered based on an internal Jones & Wagener database.

The stability analyses were done for the three waste types summarised in Table 1. The friction angle of the weakest was equal to the average slope of the steepest geometry. In addition a typical gold tailings (Heymann, 2016) and the waste properties prescribed by the Minimum Requirements for Waste disposal by landfill (DWAF, 1998) was considered. To simplify the analyses the materials were assumed to be completely dry.

Table 1. Waste types considered for the stability analyses

Waste	**Friction angle** [°]	**c'** [kPa]	**Unit weight** [kN/m³]
Waste 1	26.6	0	18
Tailings	33	0	18
Min. Req. Waste	15	25	10

3 Critical factor of safety

For the Waste 1 and tailings the lowest factor of safety was typically for sloughing failures due to the low c' or localised failure of the benches, as evident in Figure 3. These failures will not compromise the over-all stability of the facility unless it develops into progressive failures. However, progressive failures are gradual in nature and typically the operator will have sufficient time to rectify the problem before it becomes critical.

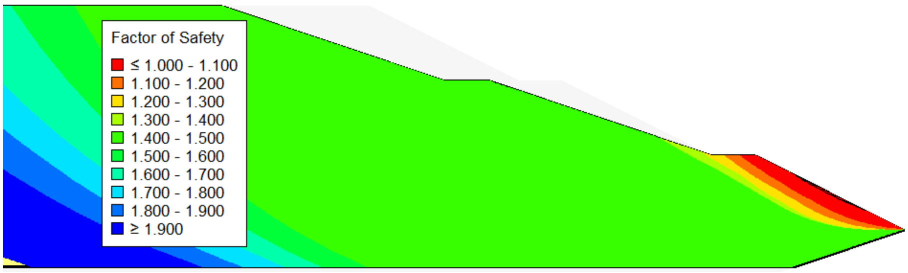

Figure 3. Slip surfaces and corresponding factor of safety for a A-A-A-2.5 m facility of Waste 1

To identify the critical F.o.S. for a given analysis the F.o.S. was plotted against average slip depth. As illustrated in Figure 4 the average slip depth calculated was equivalent to the depth of a circle segment with a volume equal to that mobilised by the slip, and a radius equivalent to that of the slip:

$$A = \frac{R^2}{2}(\theta - \sin\theta)$$

where A is the area of the slip, R the radius of the slip and:

$$\theta = 2\arccos\left(1 - \frac{d}{R}\right)$$

where d is the average depth of the slip.

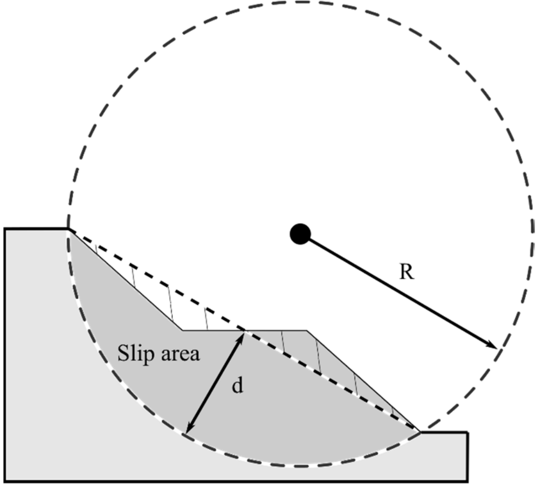

Figure 4. Calculation of the average slip depth

In Figure 5 the average slip depth versus F.o.S. is shown for one of the geometries analysed as tailings. In addition, a curve of the maximum slip depth for a given factor of safety is also shown. This curve was used to determine the critical factor of safety for each of the scenarios analysed.

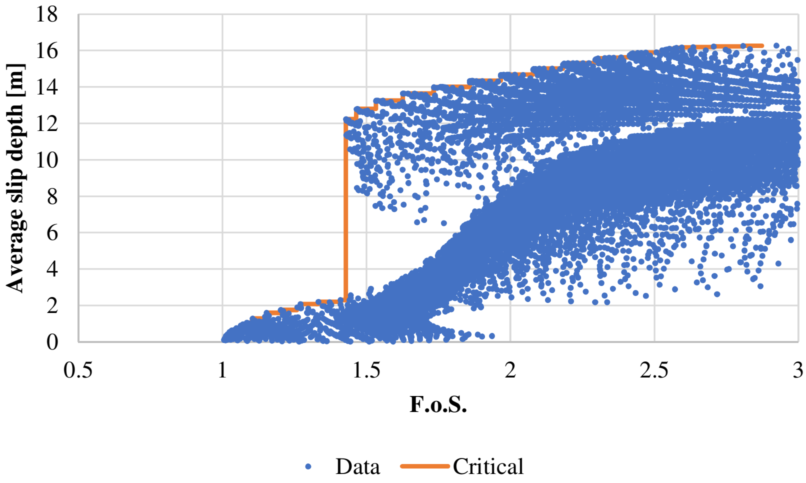

Figure 5. Average slip depth versus factor of safety for an B-A-A-2.5m Waste 1 facility

The critical deep seated slip surface can be identified by a significant increase in slip depth for a minor increase in factor of safety. All factors of safety before this point are for sloughing failures. The first deep seated failure was typically also the first failure where the slip surface extended to the liner.

Not all geometries lends itself to a curve with such an abrupt change in slip depth for a given increase in factor of safety. For some geometries the lowest F.o.S. is a deep seated failure, and thus critical. For other geometries the lowest F.o.S is for a sloughing failure but there are no abrupt increases in slip depth that can be used to identify the critical failures. For these geometries the critical slip depth, e.g. 5 m, needs to be chosen by the engineer and the corresponding F.o.S. extracted from the curve.

4 Results

A facility with 1:3 slopes for all three benches will store the lowest volume of material for an available width. The percentage increase in volume stored compared to this geometry was calculated for the other geometries. In Figure 6 the difference in critical factor of safety to the flattest slope, for all three materials is shown as a function of the increase in volume, for a given geometry. These results are for the 5 m deep basin.

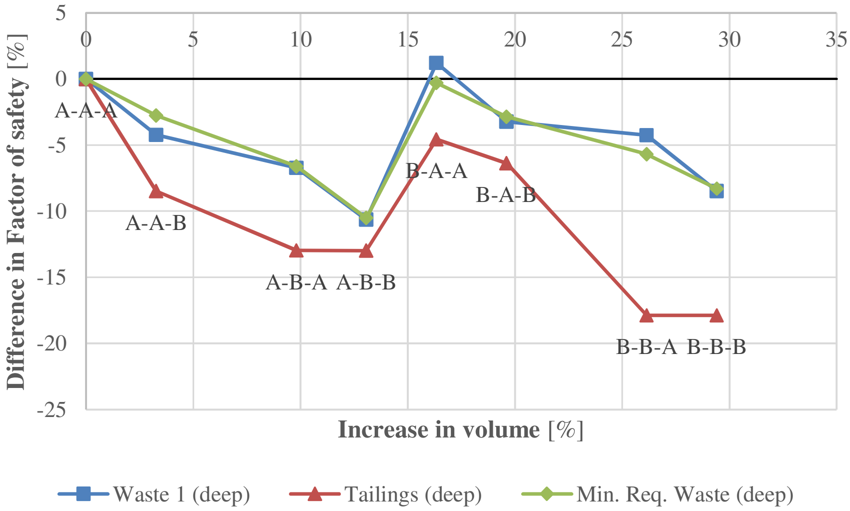

Figure 6. Difference in factor of safety from flattest geometry as a function of the increase in volume stored for a 5 m deep basin.

For the first three geometries there is a reduction in factor of safety with an increase in volume. For these geometries the slope of the bottom bench remained at 1:3 while that of the upper benches increased. The nett effect was that the mass of the active block increased and so did the forces driving failure. Consequently, the factor of safety decreased. However, when the slope of the first bench was increased to 1:2 the factor of safety increased slightly above that of the flattest slope for two materials.

By increasing the slope of the first bench the mass of the passive block is increased. As the passive block increases the resistance of the slope to failure, the factor of safety increased. Furthermore, the steeper bottom bench allows for a greater volume of material to be stored in the same width, without compromising the stability of the structure.

Due to the increased resistance of the passive block the failure is now forced through the waste body to reduce the effectiveness of the passive block. This is evident in Figure 7 where the F.o.S. is the same for the lined and unlined facilities, for the geometries where the size of the active block is increased. It should be noted that for this geometry with a flat basin increasing the size of the active block was not sufficient to increase the F.o.S. above that of the flattest geometry. However, a significant increase in volume stored was still achieved for a minor decrease in F.o.S.

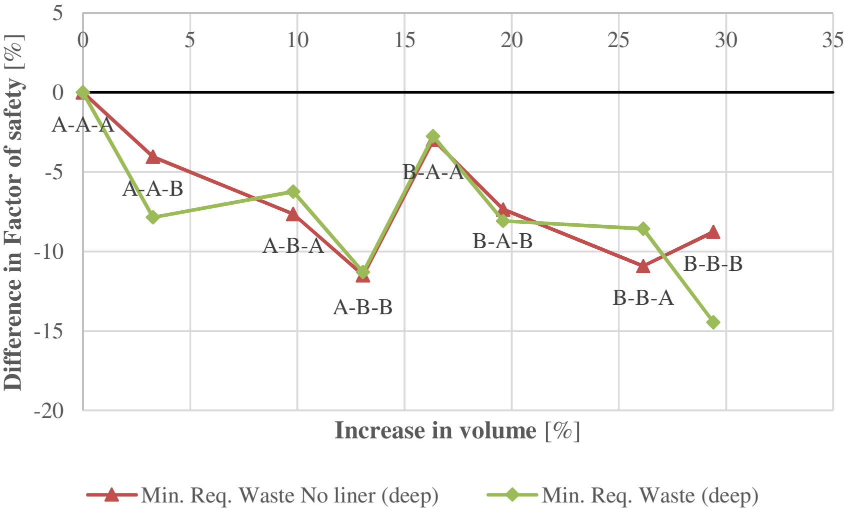

Figure 7. Difference in factor of safety from flattest geometry as a function of the increase in volume stored for a lined and unlined facility, for a 0 m deep basin.

The final geometric property that was investigated during the stability analyses was the effect of the depth of the basin. The results for Waste 1 for the different basin depths are compared in Figure 8 as an example. For all materials the F.o.S. increased for the deepest basin, when the facility was lined. For lined facilities the critical slip surface typically extends down to the basin as the shear resistance is weaker than the remainder of the facility. With a deeper basin the critical slip surface needs to extend much further through the waste to reach the weak interface. A longer slip surface implies that there is greater shear force resisting failure, and thus a higher factor of safety. This behaviour does not hold for the unlined facility as the critical slip does not necessarily extend down to the basin.

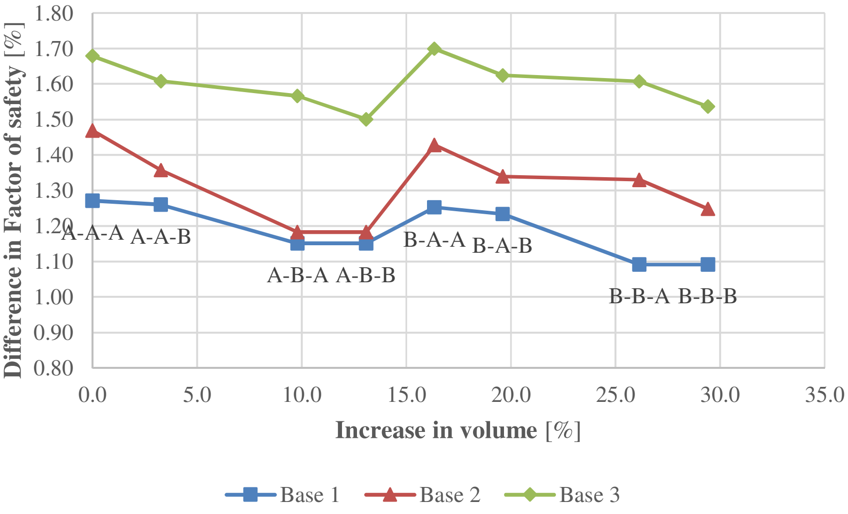

Figure 8. Effect of basin depth on factor of safety

5 Conclusions

Stability analyses of lined waste facilities were done to investigate the effect of geometry on the stability of lined waste facilities. It was found that both the stability and the capacity of the facilities can be increased by constructing the bottom bench at a steeper slope than the remainder of the facility. Consequently, the geometry with the flattest slopes is not necessarily the safest nor the most economical design.

This set of results are only applicable to the geometries and wastes considered for this analysis. For different geometries, wastes or when a phreatic surface is modelled the optimal geometry might differ. However, any geometry that increases the weight of the passive block, without changing the active block, will most likely increase the F.o.S. of the facility. Typically, this will also increase the capacity of the facility.

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