Investigation of the slope stabilization of tailings dams using geosynthetics

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ABSTRACT

The instability of tailings dams is caused by several factors which include weather extremes, overtopping, seepage, erosion, subsidence and poor construction methods. In addition, emerging mining technologies which facilitate the extraction of minerals from low grade ores also produce higher tailings volumes of very fine particle size. Problems associated with fine grained tailings include reduced permeability and shear strength which consequently increase the risk of dam failure. The stability of tailings dams can be improved by reinforcing the impoundments with geosynthetics. A geosynthetic should only be used for tailings dam reinforcement if it has sufficient chemical resistance, strength and durability. A series of tests is therefore necessary to assess the effectiveness of reinforcing specific tailings with a given geosynthetic. In this study, interface direct shear strength tests were conducted to assess the frictional resistance between platinum mine tailings and different types of geosynthetics. Using the test results a reliability slope stability analysis was conducted. It was found that reinforcing the dam with geosynthetics permitted an increase in the height of the dam dykes and slope by a factor of 1.3 and 2.3 respectively with 0% probability of failure. This demonstrated that geosynthetics reinforced tailings dams are not only more stable but they can be constructed at the optimum geometry which fully utilizes the allocated land. Consequently, stabilizing tailings dams with geosynthetics also reduces their construction and maintenance costs.

Key words: Interface shear strength, reliability, probability of failure, reliability index

1. INTRODUCTION

The frequency of tailings dam failures has by no means decreased in the last decade. Despite the abundance of engineering software and equipment used to design and analyze the impoundments, tailings dams continue to collapse world over. Some of the major tailings dam failures in recent years include Cadia – Australia, Satemu - Myanmar and Mariana and Brumadinho – Brazil. Also, a study in China by Yin et al. (2004) revealed that most tailings dams in the region which were less 25m high were at risk of failing. A single tailings dam failure can potentially lead to loss of life, land and water contamination and extensive damage of infrastructure. It has become apparent that the traditional construction of tailings dams cannot fully ensure the stability of the impoundments.

Unlike conventional earth dams which are constructed using suitably competent material, the stability of tailings dams is mainly dependent on the tailings shear resistance. Coarse tailings have higher shear strength and permeability than fine tailings. Deposition methods like cycloning and spigotting seek to exploit these properties by discharging the coarse tailings on the dam wall and the fine tailings on the beach. The permeable coarse tailings control the buildup of pore water pressure and seepage forces on the wall. The fine tailings retain the processing water which is then recycled back to the plant. To increase mineral production, mines use equipment which can process low grade ore and this has also resulted in increased volumes of fine grained tailings. The decrease in percentage of coarse tailings reduces the dam's strength and hydraulic gradient which in turn increases the risk of failure.

Irregularities of seasonal patterns, melting of polar ice caps and depletion of the ozone layer are evidence of climatic changes. As a result of climate change weather extremes like earthquakes and floods now occur more frequently and severely. Unfavorable weather conditions undermine the stability of tailings dams hence most failures are triggered by their occurrence. The majority of slides occur during or soon after heavy rainfalls. Due to their lack of compaction, tailings dams are susceptible to liquefaction. The movements caused by earthquakes increase pore water pressure in the dam which reduces the strength and stiffness of the tailings causing them to liquefy. Eventually it will be nearly impossible for tailings dams to be safely constructed without reinforcement.

2. REINFORCEMENT OF TAILINGS DAMS

Geosynthetics have emerged as one of the effective tailings dam reinforcement materials. Other materials of high tensile strength like steel cannot be used to reinforce tailings dams where the tailings are corrosive. In addition to chemical resistance, geosynthetics have the advantage of being cost effective, adaptable and easy to install. Reinforcing with geosynthetics results in a system that has both compressive and tensile resistance which improves the stability of the impoundments. While there has been a rise in the use of geosynthetics, their incorporation in tailings dams has not been met without reservations. Major engineering bodies like the United States Army Corps of Engineers (USACE) do not permit the use of geosynthetics in locations that are critical to the safety of tailings dam and inaccessible for replacement (FEMA, 2008). Their main concern is that tailings impoundments exert higher stresses and seepage gradients which geosynthetics may not be able to withstand. The USACE only approves the use of geosynthetics provided that they can be easily accessed for inspection and repair.

A study by Grubb et al. (2001) reported that polyester and polypropylene geosynthetics which were used in cyanide infused gold tailings lost 40% of their strength in 360 days. This further validates the apprehension of incorporating geosynthetics in tailings impoundments. However, geosynthetics have also performed well in a number of tailings dams which include Richards Bay -South Africa, Rosedale -Australia and Collahuasi -Chile. While the concerns of using geosynthetics are valid, the successful projects in which they have been implemented demonstrates their competence. In order to guarantee their capability the geosynthetic-tailings interaction should be analyzed and well understood prior to their application.

3. FACTORS THAT AFFECT THE PERFORMANCE OF GEOSYNTHETICS

There are several factors that may undermine the performance of geosynthetics when installed in tailings dams. A geosynthetic may elongate under constant loading in a process known as creep. This stress induced distortion will result in the geosynthetic losing its strength and failing to resist the stresses it was designed for. Geosynthetics can also undergo environmental degradation when exposed to fluids of either high or low pH, high temperatures or Ultra Violet Radiation (UVR). For tailings reinforcement applications the risk of UVR degradation is minimum but the potential for hydrolysis is high. Hydrolysis occurs when the geosynthetic comes into contact with an acidic or alkaline fluid. Emerging geosynthetic products have high chemical resistance which minimizes this risk.

Geosynthetics can be easily damaged prior to installation and/or after installation. Pre-installation damage can occur during production, transportation or on site. Quality control measures are needed to ensure that geosythentics are not contaminated, punctured or torn during installation. Onsite activities that can damage geosynthetics include poor loading and offloading procedures, use of forklifts which puncture the materials and dragging them on the ground. Post installation damage of geosynthetics can be caused by internal slope movements and ground movements due to mine subsidence. There is also the possibility of the geosynthetic being raptured by animal intrusion or plant roots. In light of these risks the ultimate strength of geosynthetics is normally reduced to its long term design strength (LTDS). The LTDS is computed by applying reduction factors due to creep, installation damage, chemical and biological durability. The design of reinforced tailings dams is governed by the LTDS and not the ultimate tensile strength. Application of the reduction factors can reduce the ultimate strength of the geosynthetics by up to 16 times (Koerner, 2005). This very conservative method ensures a safe design.

4. LABORATORY TESTS

This study investigated the application of different types of geosynthetics to reinforce platinum mine tailings; namely a geogrid, a geocomposite and a geotextile. The geogrid was an extruded polypropylene sheet with triangular holes. The holes allow the geogrid to interlock with the surrounding material. Geogrids are exclusively manufactured for reinforcement. The geocomposite consisted of high strength polyester yarns arranged in the machine and cross directions to form a grid that is mechanically bonded to a 150g/m^2 polyester non-woven needle punched staple filament geotextile. This type of geocomposite is also mainly used for reinforcement. The geotextile comprised of two sets of parallel yarns or tapes which are inter-lapped to form a planar structure. Its high strength and permeability made it appropriate for tailings dam reinforcement. Laboratory tests were conducted to determine the geotechnical properties of the tailings and the geosynthetic – tailings interface characteristics.

4.1 *Soil classification tests*

The hydrometer (sedimentation) test was used to determine the particle size distribution because the tailings were predominantly fine grained. From the gradation curve it was determined that the tailings were silty clay material. Both the Casagrande and cone penetrometer test were used to determine the liquid limit. The test results showed the tailings did not have consistency limits and this behavior is normally associated with soils of low plasticity. The tailings compaction was tested using the Proctor method. The maximum dry density was found to be 2.16Mg/m^3 at an optimum moisture content of 13.5%. The specific gravity was measured using the small pycnometer method which is the most accurate test for fine material. The tailings had a fairly high specific gravity of 3.66. Figure 1 illustrates the particle size distribution chart.

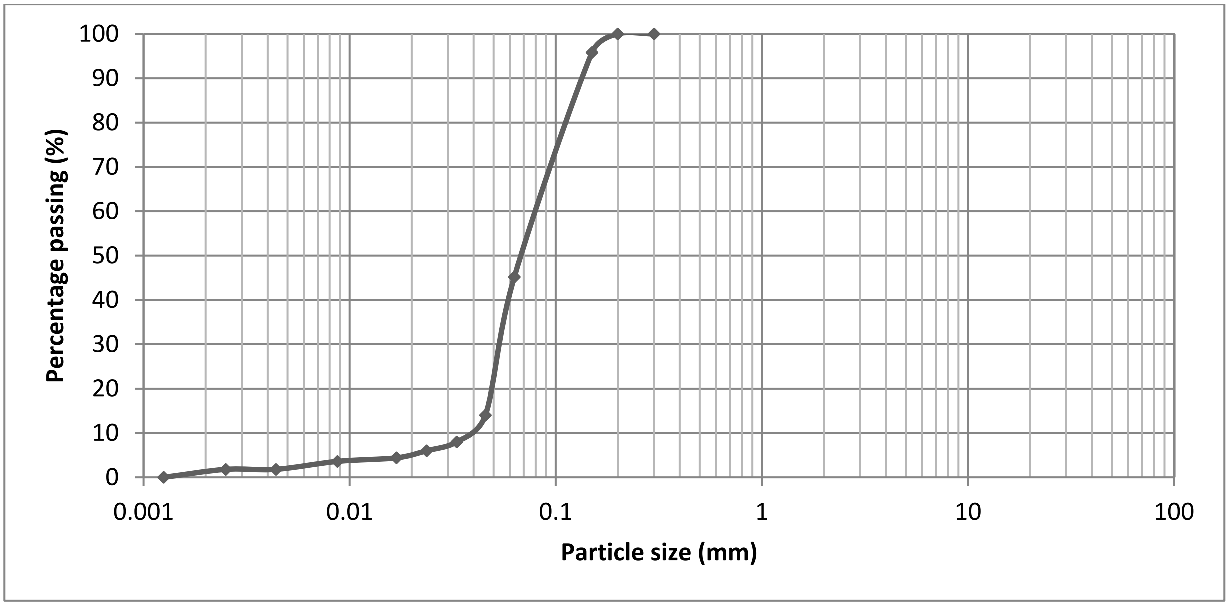

Figure 1. Platinum tailings particle size distribution chart.

4.2 *Shear strength test*

The shear strength characteristics of the tailings were determined using the direct shear test. The test was conducted under Consolidated Undrained (CU) conditions after ASTM D3080. The procedure involved subjecting a square prism of tailings to a normal pressure while it was laterally restrained and sheared along a horizontal plane. The tailings' shear resistance as the top half slides over the bottom was measured at regular intervals of displacement. Three tests were conducted at normal loads of 50kPa, 100kPa and 200kPa. The tailings' cohesion was found to be 1.98kPa while the angle of internal friction was 37.2^o. Figure 2 shows the direct shear strength test equipment which is automated to a computer that provides the readings and also plots the failure envelope. The failure envelope is presented in Figure 3.

Figure 2. Direct shear test equipment.

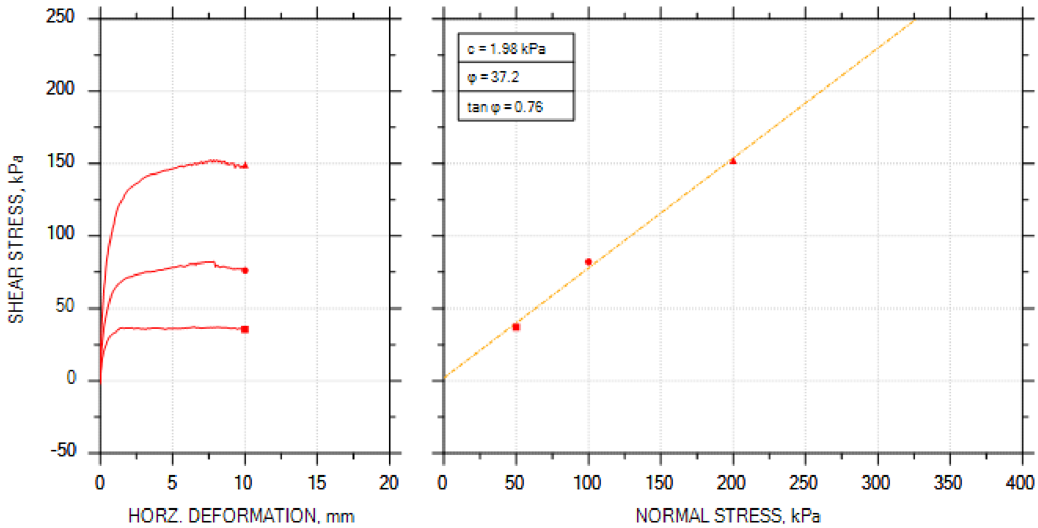

Figure 3. Tailings failure envelope.

4.3 *Interface shear strength test*

The geosynthetic – tailings interface direct shear strength was determined using a large shear box. The test was also conducted under CU conditions and the equivalent three normal pressures of 50kPa, 100kPa and 200kPa were applied. The process involved measuring the resistance as the tailings slide over the geosynthetic at regular intervals of displacement. The test results showed that the geocomposite – tailings interface yielded the highest cohesion of 34.8kPa. This was a significant increase from the initial tailings value of 2kPa. This indicated that the frictional resistance between the tailings and the geocomposite was much higher than that of unreinforced tailings. The geogrid – tailings interface had the lowest cohesion of 8.11kPa but its friction angle of 39.9º was the highest. The geotextile-tailings interface had the lowest friction angle of 27.9º, implying that of the three geosynthetics, the geotextile had the least interface tensile resistance with the tailings. Figure 4 presents the large shear box test equipment that was used, which is also automated to a computer. The failure envelopes for the tailings – geosynthetic interface are illustrated in Figure 5.

Figure 4. Interface direct shear strength test equipment.

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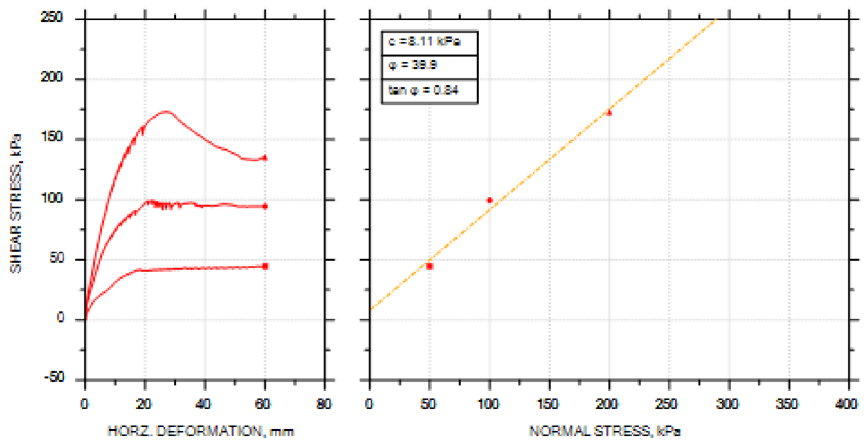
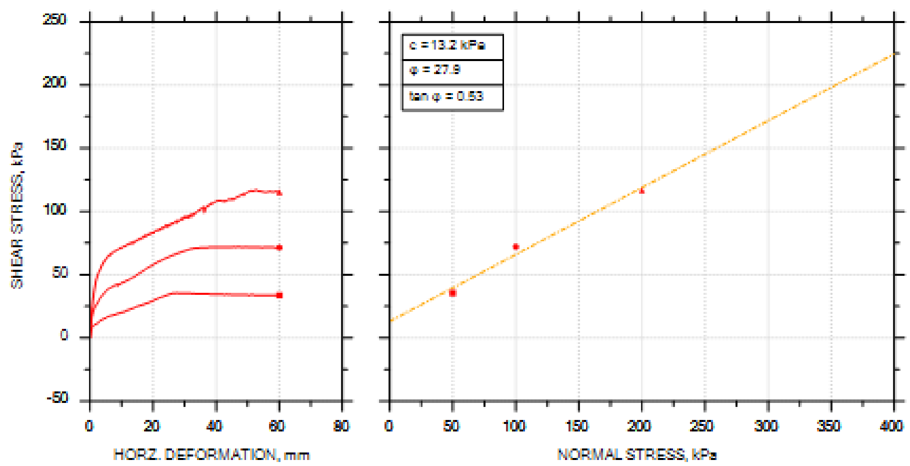
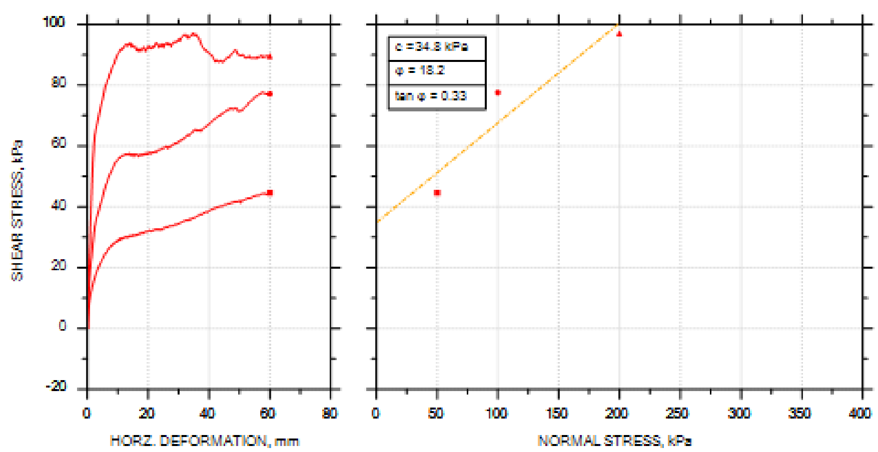


a) Geogrid-tailings interface failure envelope



b) Geotextile-tailings interface failure envelope.



c) Geocomposite-tailings interface failure envelope

Figure 5. Geosynthetic-tailings interface direct shear strength characteristics.

5. SLOPE STABILITY ANALYSIS

Conventionally, the stability of tailings dams is analyzed using Limit Equilibrium Methods (LEMs). The main shortcoming of LEMs is that they assign single deterministic soil parameter values whereas in reality soils and tailings are heterogeneous and anisotropic. Due to this limitation, the Factor of Safety (FS) which is derived from LEMs may not be a true representation of actual site conditions. This could also explain the collapse of tailings dams that would have been analyzed and deemed to be stable using the LEM. Contrary to the LEM, reliability methods address variability and uncertainty by defining soil parameters in terms of their mean value and standard deviation.

In addition to the FS, reliability methods also determine the Probability of Failure (PF) and the reliability index of tailings dams. The probability of failure is the probability of obtaining a FS which is less than 1. The PF ranges from 0 to 1. The reliability index (β) is a function of the mean value (μ) and the standard deviation (σ) as expressed in Equation 1. A dam with a low probability of failure will have a high reliability index and vice-versa. The variability of soil parameters can either follow a normal or log-normal distribution. The reliability index is named after the distribution profile using the terms Normal Reliability Index (NRI) or lognormal reliability index (LRI). Previous studies have shown that tailings parameters can follow both the normal and lognormal distribution hence either can be used in the analysis (Beacher and Christian, 2003).

$$\beta = \frac{\mu - 1.0}{\sigma} \qquad [1]$$

where: β = reliability index
μ = mean value
σ = standard deviation

In this study the Monte Carlo (MC) reliability method was used to determine the stability of the tailings dam. The MC method is used to solve problems that have random variable. The slope stability analysis was performed using Roc Science software. The software has an inbuilt random number generator which provides uniformly distributed numbers for the given soil parameters using their mean and standard deviation. The proposed tailings dam was to be constructed across a valley over an area of 39ha. The dam consists of a bedrock foundation, starter dam and tailings. It was designed to have 7m high dykes at a slope of 30º and a crest width of 5m. The slope stability analysis yielded a FS of 1.791, with a PF of 0% and a LRI of 6.082. Under these conditions, the dam is in a stable state. Figure 6 illustrates the MC reliability slope stability analysis.

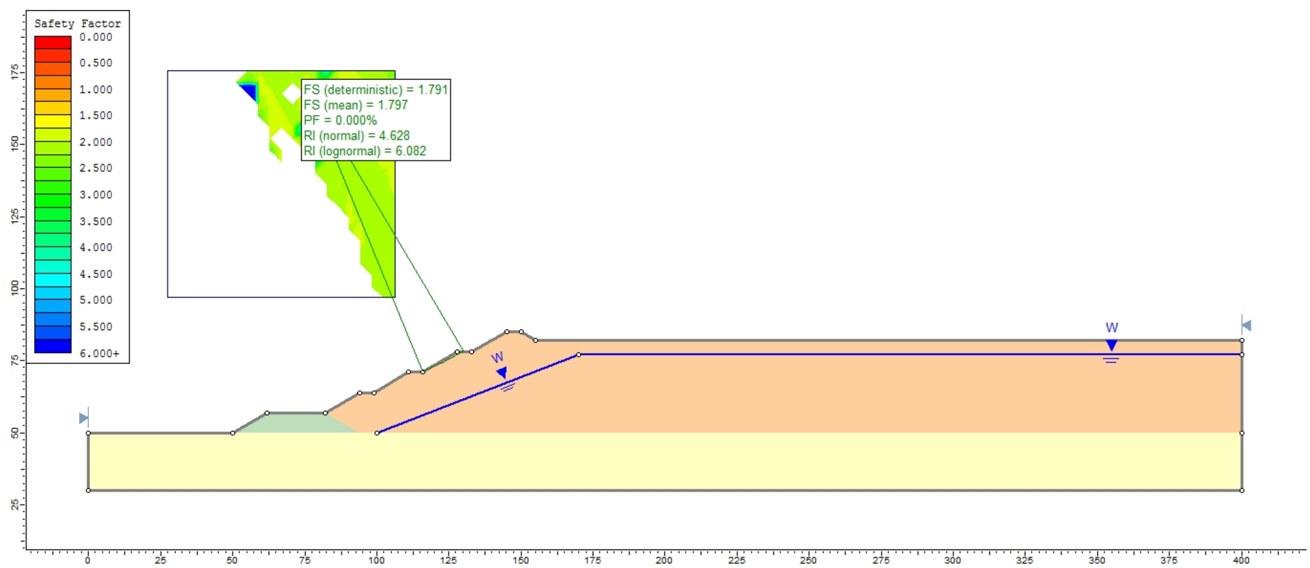


Figure 6. Monte Carlo reliability slope stability analysis of proposed tailings dam.

Most tailings dams are constructed at a gentle slope of 25-30º to enhance their stability. Where the tailings are too weak, the slope can be as low as 10º. Gentle slope tailings dams quickly diminish their capacity forcing the mine to construct a new dam within a shorter period. Apart from this increasing the mine operational costs, a new dam will consume more land which could have been used for productive purposes. Not only do tailings dams distort the natural aesthetics of their environs but they are also a potential hazard. They may cause air, land and water pollution if not handled properly. World over stringent environmental regulations constrain land which can be occupied tailings dams. The design and construction of the impoundments should be such that they fully utilize their allocated land. This can be achieved by increasing the slope. Geosynthetics reinforced slopes can be safely constructed at steep angles of up to 70º. Figure 7 presents the slope stability analysis of the dam when constructed at a slope of 70º.

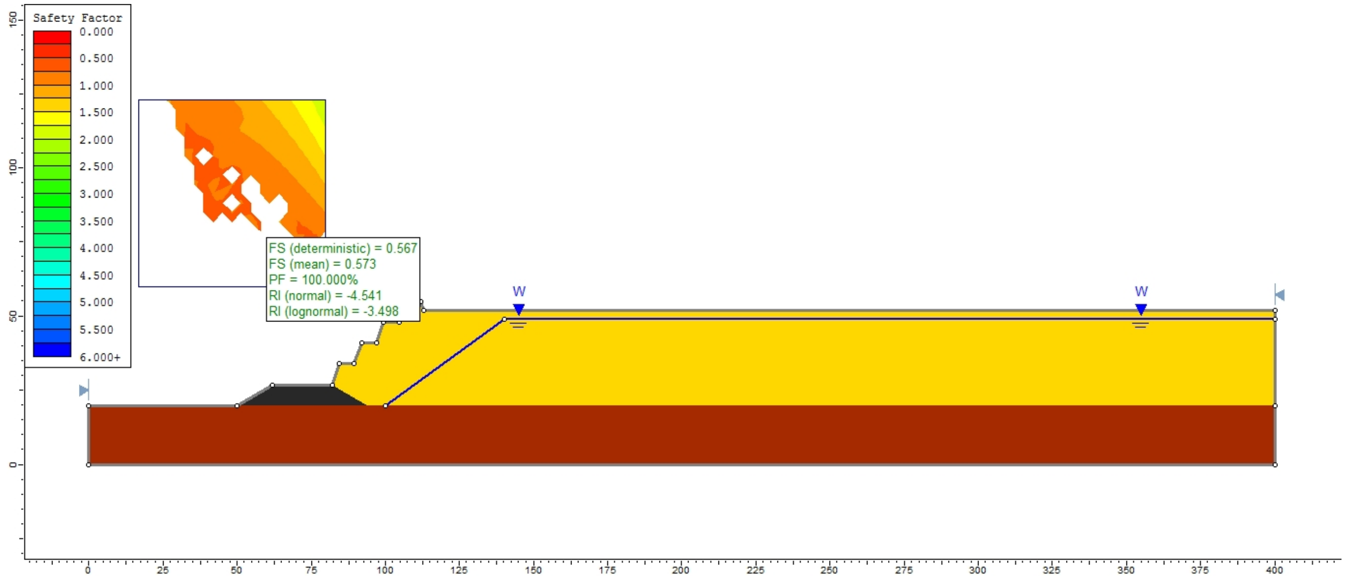


Figure 7. Slope stability analysis of the tailings dam at a slope of 70º.

Increasing the slope reduces the safety factor reduces to 0.567, increases the PF to 100% and decreases the LRI to -3.498.In order for tailings dams to be safely constructed at the optimum geometry that maximizes land usage they must be stabilized. Tailings are strong in compression but weak in tension. Geosynthetics which are manufactured for reinforcement have high tensile resistance and are designed to distribute the load over a large area. Introducing a geosynthetic results in a hybrid system that has both compressive and tensile resistance. The test results of the interface direct shear tests between the tailings and geosynthetics are shown in Table 1.

Table 1. Shear strength characteristics of geosynthetics reinforced tailings.

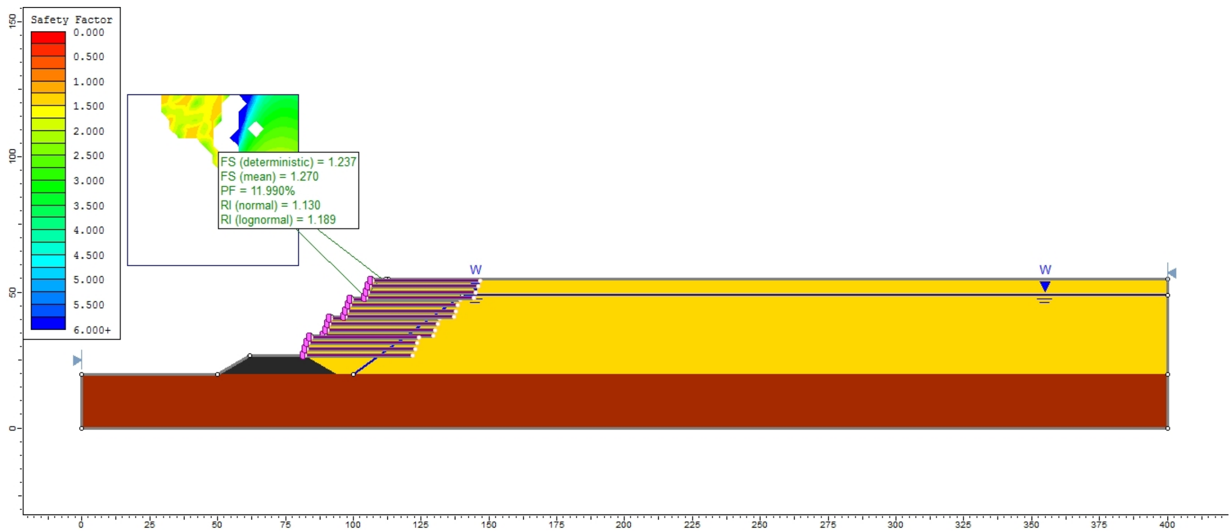
Geosynthetic	Cohesion (kPa)	Interface friction angle (º)
Geocomposite	34,8	18,2
Geogrid	8,1	39,9
Geotextile	13,2	27,9

A reliability slope stability analysis of the reinforced tailings dam using each geosynthetic was conducted. In all cases the geosynthetic layers were spaced at 2.3m and had a length of 40m. Overall, it was found that stabilizing tailings dams with geosynthetics improved their stability. All three geosynthetics yielded a safety factor which was greater than 1.0. The geotextile reinforced tailings dam yielded the lowest FS of 1.237 with a PF of 11.990% and a LRI of 1.189. While a safety factor which is greater than 1 denotes stable conditions, the Canadian Dam Association (CDA) categorically states that the minimum permissible safety factor for tailings dams is 1.3. Based on that, the geotextile reinforced tailings dam was classified as unstable. The geocomposite reinforced tailings dam had a FS of 1.326, a PF of 6.660% and a LRI of 1.527. Had the LEM been used to analyze the dam's stability, the geocomposite reinforcement would have been considered to be adequate based on a FS which is greater than 1.3. Using the more refined reliability method showed that the dam still had a high failure potential.

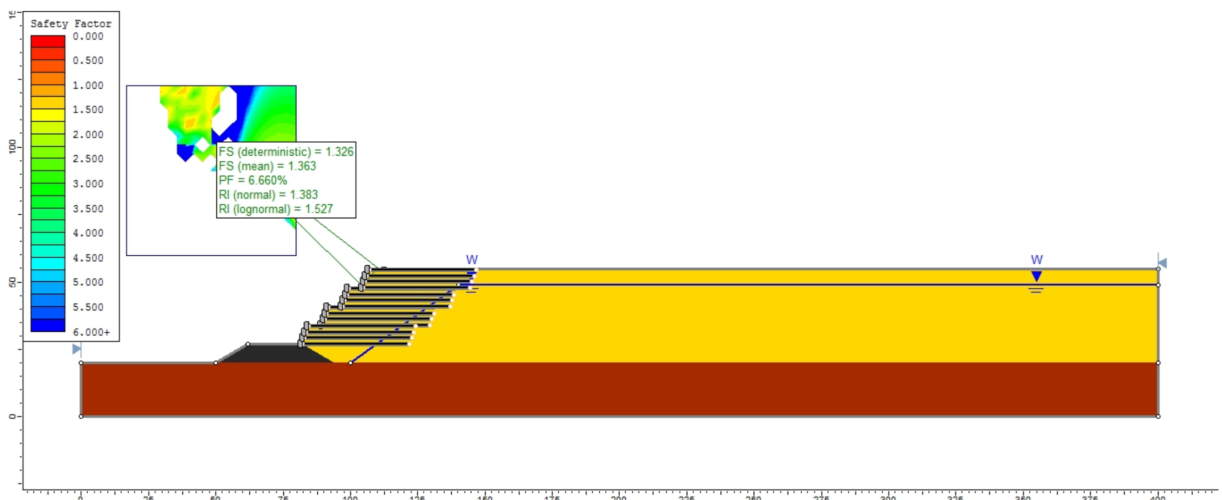
The USACE (1997) provides a classification framework of the expected performance of tailings dams according to their PF and LRI. The expected performance ranges from high for a tailings dam with a LRI of 5.0 and a PF of $3x10^{-7}$ to hazardous for a dam with a LRI of 1.0 and a PF 0.16. Using this framework the geocomposite reinforced tailings dam's expected performance is classified as "unsatisfactory". This further demonstrates the importance of using reliability methods in analyzing the stability of tailings dams. By incorporating soil heterogeneity and uncertainty, reliability analyses are more representative of actual site conditions. Table 2 shows the USACE (1997) classification of expected tailings dams performance while Figure 8 illustrates the MC reliability slope stability analysis for the three geosynthetics.

Table 2. Classification of expected tailings dam performance (USACE, 1997).

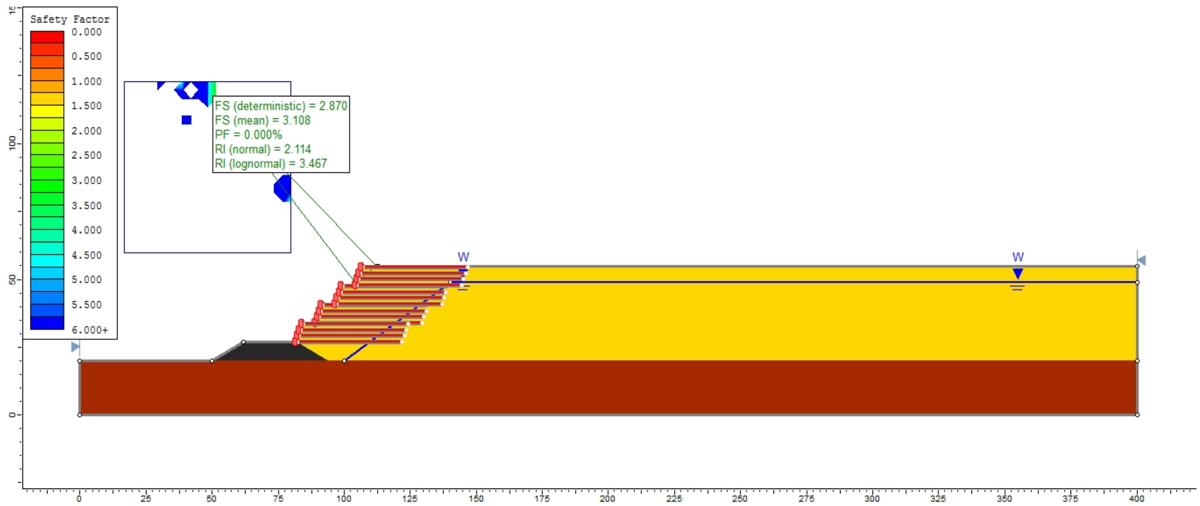
Expected performance	Lognormal reliability index	Probability of failure
High	5,0	0,0000003
Good	4,0	0,00003
Above average	3,0	0,001
Below average	2,5	0,006
Poor	2,0	0,023
Unsatisfactory	1,5	0,07
Hazardous	1,0	0,16



a) Geotextile reinforced tailings dam



b) Geocomposite reinforced tailings dam



c) Geogrid reinforced tailings dam

Figure 8. Reliability slope stability analysis of geosynthetics reinforced tailings dam.

The geogrid reinforced tailings dam was the most stable with a FS of 2.87, a PF of 0.000% and a LRI of 3.467. Under these conditions the geogrid reinforced tailings dam is considerably stable. There is room to even expand the dam further by increasing the height of each staged dyke from 7m. Figure 9 illustrates the reliability slope stability analysis of the tailings dam with 9.2m high dykes. Increasing the height of the dykes reduces the FS and LRI to 1.804 and 3.201 respectively while the PF increases to 0.07%. In the expected performance classification table, the tailings dam remains at the above average to good level, therefore its stability is uncompromised. The improvements in the dam geometry that can be achieved by reinforcing the tailings dam with geogrids are shown in Table 3.

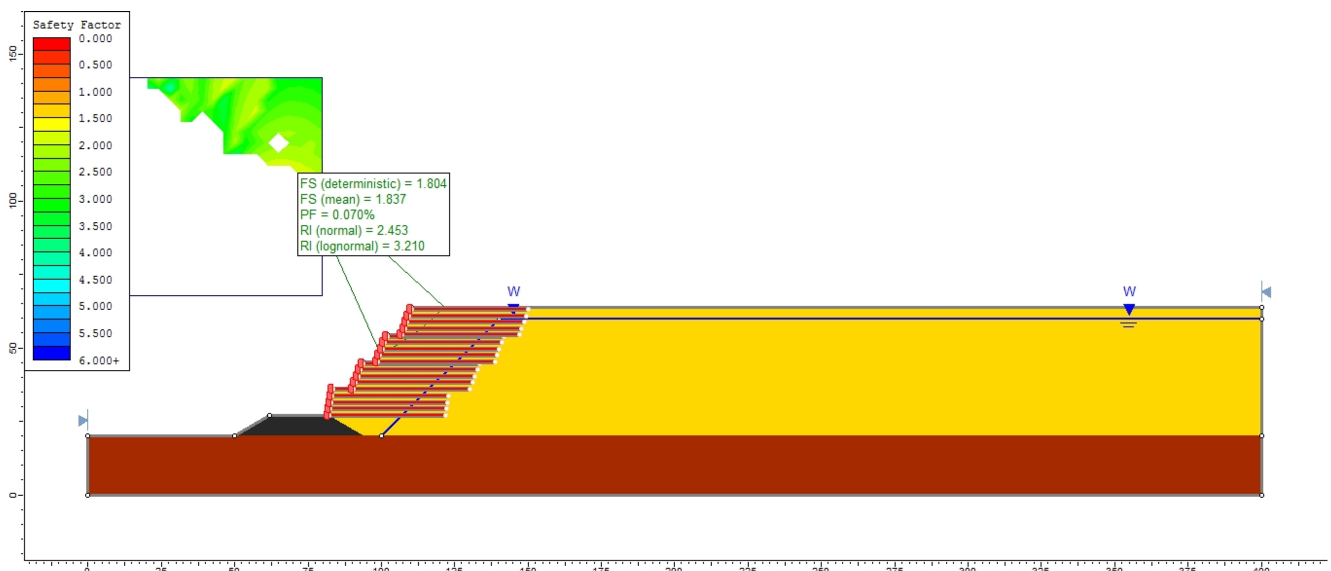


Figure 9: Reliability slope stability analysis of geogrid reinforced tailings dam with 9.2m high dykes.

Table 3. Tailings dam parameters before and after geogrid reinforcement.

	Dyke height (m)	Slope (º)
Before reinforcement	7,0	30
After reinforcement	9,2	70
Improvement factor	1,3	2,3

6. CONCLUSION

To meet the high demand for minerals, some mines have transitioned to deep level mining and the exploitation of lower grade ores. This leads to the production of higher tailings volumes and the fast rise of tailings dams. These factors, coupled by inclement climate changes, subsidence and poor construction methods tend to undermine the stability of the impoundments. It will become much more difficult for tailings dams to remain stable without reinforcement. Geosynthetic properties which include high tensile strength and chemical resistance, cost effectiveness and pliability render them suitable for tailings dam stabilization. The slope stability analysis in this investigation was undertaken using the Monte Carlo reliability method. Reliability methods incorporate the uncertainty and variability of tailings parameters. They define the dam's stability in terms of its probability of failure and reliability index. This results in a more accurate representation of actual site conditions. The study demonstrated that reinforcing the dam with geogrids not only improved its stability, but it permitted an increase in the height and slope of the dykes by a factor of 1.3 and 2.3 respectively. At a steep slope of 70º and a dyke height of 9.2m, the geogrid reinforced tailings dam had a probability of failure of 0.07% and a log-normal reliability index of 3.201. Optimization of the dam geometry improves land utilization which extends the dam's operation life and reduces construction costs. While the geogrid satisfactorily met the stability requirements, there is need for additional tests to assess chemical inertness, durability and pull-out resistance.

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