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Application of geogrids in the slope stabilization of tailings storage facilities: A case study of an upstream tailings dam

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ABSTRACT

In response to the global upsurge in tailings dam failures, there has been an intensification in the prohibition of upstream construction in a bid to curtail the disasters. Brazil, Chile, Ghana and Peru are some of the countries where the upward construction of tailings storage facilities has been banned. This interdiction is contentious because some of oldest tailings storage facilities which are located around the world including USA and South Africa (SA) were constructed using the upstream method and have remained stable for more than a century. Mainly due to cost effectiveness, the upstream method has been the most popular tailings dam construction technique. However, in the present decade, from 2020, at least 14 major failures have been reported globally. The heightened failure rate demands measures which can be used to ensure the safe construction of the impoundments. This study investigated the slope stabilization of an upstream tailings dam using geogrids. Due to their high tensile strength and resistance to chemical degradation, geogrids can be used to improve the shear strength of tailings storage facilities. In this study, the slope stability analysis was undertaken using the Monte Carlo reliability method. It was found that the geogrid reinforcement system approximately doubled the safety factor of the facility, reduced the probability of failure and increased the reliability index from a negative (-1.45) to a positive (+7.18). The stabilization of tailings dams with geogrids can significantly reduce the risk of dam failure and the consequential environmental, financial and humanitarian impacts.

Key words: tailings dam, upstream, geogrids reinforcement, slope stability analysis, Monte Carlo

1 INTRODUCTION

Morgenstern (2018) observed that the construction of upstream tailings storage facilities (TSFs) was acceptable provided that key principles in the design, construction and operation of the facilities were adhered to. The construction of upstream tailings dams requires minimum fill material and while this reduces the construction costs, it heightens their vulnerability (Fourie et al., 2022). This is because the stability of upstream impoundments is dependent on the tailings gaining sufficient strength. In sharp contrast, in the downstream and centerline methods, the downstream slope rests on the foundation soil which provides a support system for the dam (Vick, 1983). In this configuration, the stability of the storage facility is not influenced by the tailings strength. However, tailings dam statics over a 100-year period from 1917 to 2017 revealed that with the exception of unknown dam types, downstream and centerline facilities contributed to 24% of the failures (Riskope, 2017). Therefore, an embargo on upstream construction may not necessarily alleviate failure because TSFs can still collapse regardless of the construction method.

The main causes of tailings dam failures include slope instability, seismic actions and overtopping (Azam & Li, 2010, Hamade, 2013); these three account for at least 50% of reported incidents. Overtopping occurs when the water level in the facility exceeds the dam crest causing a spillage which often leads to dam breach. Seismic events can be naturally induced by an earthquake or initiated by anthropogenic factors such as vibrations from machinery or blasting. Slope instability ensues when overturning moments exceed resisting moments resulting in a slip failure. Other failure causes include structural inadequacies, seepage forces, foundation failure, internal erosion (piping) and external erosion (Kalumba & Mudenge, 2019). Figure 1 presents statistics of tailings dam failure causes based on 300 global case histories from 1917-2022.

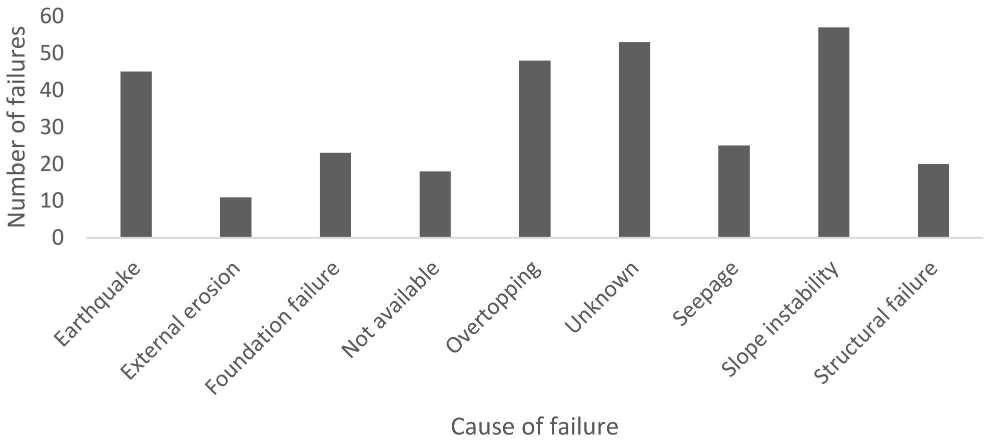


Figure 1. *Tailings dam failure causes*

The data underscores the fact that slope instability is the main cause of TSF failures. The collapse of a TSF is often a catastrophic event entailing loss of life and environmental and infrastructural damage. The Jagersfontein TSF collapse in SA (2022) resulted in 3 fatalities which was considerably less than the Hpakant, Myanmar (2020) and Brumadinho, Brazil (2019) death tolls of 126 and 267 respectively. However, the estimated 20x10^6 m^3 of tailings which flowed from Jagersfontein TSF contaminated Kalkfontein dam which connects to the 200km Riet River; a national freshwater ecosystem. The contamination could potentially become the most severe case of environmental pollution in SA. To mitigate TSF failures, one of the techniques which can be utilized is increasing their resistance to shear failure through reinforcement.

Geogrids; polymeric geosynthetic materials formed by a network of integrally connected elements with apertures greater than 6.35mm, are exclusively manufactured for reinforcement (Koerner, 2005). There has been widespread usage of geogrid reinforcement in various infrastructures which include pavement construction, retaining walls and embankments (Koerner & Soong, 2000; Sasaki et al., 2004; Koerner, 2005). The benefits of reinforcing slopes with geosynthetics include increased shear strength and bearing capacity, affordability and maximized land usage. It would be beneficial for geogrid reinforcement to also form routine practice in tailings dam design and construction, particularly in upstream facilities (Mudenge & Kalumba, 2022). This study investigated the performance of geogrids in the stabilization of an upstream TSF comprising of 4 raises.

2 MATERIAL CHARACTERISATION

The tailings were obtained from a gold mine which had reached the capacity of the existing TSF and intended to construct a new facility. At least 5 sampling points (S1-S5) which represented the range of material variability were identified. Laboratory tests were performed on the samples to determine the geotechnical parameters. Classification tests which include particle size distribution, consistency limits, specific gravity, maximum dry density and optimum moisture content were performed after BS1377: Part 2. The results indicated that the tailings were non-plastic (NP)and predominantly consisted of silty sand (SS) and clayey silt (CS). The measured parameters were consistent with the expected range of values of hard rock tailings (ICOLD, 2017). The tailings shear strength was determined using the triaxial test following ASTM D4767 and the tailings-geogrid interface characteristics were measured using the large shear box after ASTM D3080. The geogrid is illustrated in Figure 2 and Table 1 presents its specifications. The laboratory test results are summarized in Table 2.

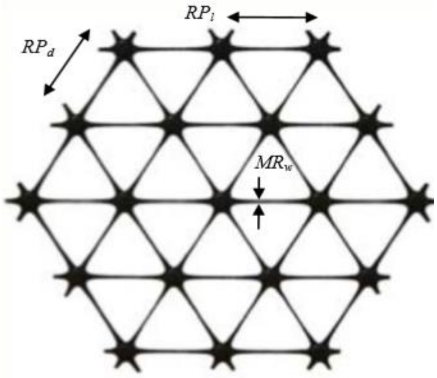


Figure 2. *TriAx TX 160 (Tensar, 2022)*

Table 1. *TriaAx TX 160 mechanical properties (Tensar, 2022)*

Geometrical	Rib pitch: Longitudinal (RP$_l$); Diagonal (PR$_d$) (mm)	40; 40
	Mid Rib: width (MR$_w$); longitudinal (MR$_l$) (mm)	1.3; 1.1
Mechanical	Junction efficiency (%)	90
	Aperture stability (N.mm/deg @ 500N.mm	390
	Isotropic stiffness ratio	>0.75
	Mean radial secant modulus at low strain (kN/m @ 0.5% strain)	455 50
Durability	Resistance to chemical degradation	96%
	Resistance to weathering	98%
	Resistance to oxidation	90%
	Resistance to installation damage	>87%

Table 2*. Laboratory test results*

Test	**Standard**	**Results**				
		S1	**S2**	**S3**	**S4**	**S5**
Hydrometer	BS1377: Part2	SS	CS	SS	CS	SS
Cone penetrometer	BS1377: Part2	NP	NP	NP	NP	NP
Specific gravity	BS1377: Part2	3.1	3.8	3.6	4	2.9
Compaction	BS1377: Part2					
Maximum dry density (kN/m^3)		20.7	18.4	22.8	19.2	20.1
Optimum moisture content (%)		12.4	11.6	13.1	16.2	14.8
Shear strength	ASTM D4767					
Friction angle (°)		40.2	33.2	39.7	31.4	38.0
Cohesion (kPa)		0.0	11.2	1.5	8.9	0.0
Geogrid-tailings interface	ASTM D3080					
Friction (°)		44	37.5	42.0	39.8	41.4
Adhesion (kPa)		7.1	18.0	9.0	15.0	6.7

3 SLOPE STABILITY ANALYSIS

3.1 Material variability

The main limitation of the conventional limit equilibrium methods (LEMs) used in the slope stability analysis of tailings dams is their inability to account for material variability. Factors which influence the variability of tailings include lithological heterogeneity from the parent ore and the effect of spatial soil variability which is caused by changes in confining pressure with dam rise. A study by Morgenstern (2000) revealed that structures which had been analyzed using LEMs yielded inaccurate results for 70% of the considered cases. Therefore, the factor of safety (FS) may not necessarily be an accurate representation of actual site conditions. In this study, the Monte Carlo (MC) reliability method was used to analyze the stability of the tailings dam. The basic concept of the MC method is the use of random sampling to determine the probability of occurrence. Reliability methods address material variability by defining soil parameters in terms of their coefficient of variation (COV) which is a measure of the spread of data with respect to the mean. The COV yielded a more representative spread of parameters. Table 3 presents the statistical distribution of the parameters which were used in the MC analysis. Generally, a COV greater than 0.3 shows a high level of variance. From the data set, it can be seen that the values of the cohesion and adhesion with a COV of 1.1 and 0.4 respectively were highly variable while the COV of the friction angle and density was within acceptable limits at 0.1. Baecher and Christian (2003) concurred that the cohesion COV tends to be higher than that of the friction angle.

Table 3. *Statistical distribution of parameters*

Material	**Parameter**	**Mean**	**Standard deviation**	**COV**
Tailings	Density (kN/m^3)	20.2	1.5	0.1
	Friction angle (°)	36.5	3.6	0.1
	Cohesion (kPa)	4.3	4.8	1.1
Tailings-geogrid interface	Friction angle (°)	40.1	2.2	0.1
	Adhesion (kPa)	11.2	4.5	0.4

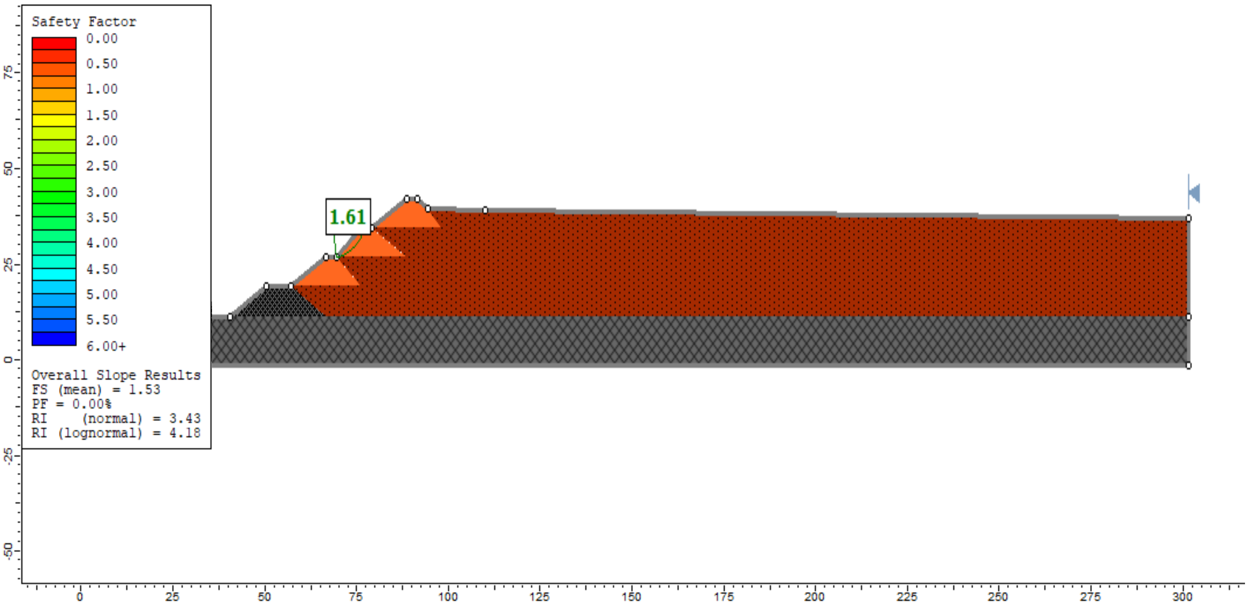
3.2 Slope stability analysis of unreinforced tailings dam

The slope stability analysis of the TSF was conducted under both drained and undrained conditions using RocScience Slide 2 software. This software was selected for its in-built random number generator which generates values for the parameters in the MC analysis. The slope was first evaluated deterministically for each set of realizations for all random variables to compute the probability of failure (PF) and reliability index (RI). The Spencer LEM was used for the deterministic analysis. The upstream tailings dam geometry consisted of 4 rises including the starter dyke which was composed of imported granular material. The dykes had a height of 6m and a slope of 25°. Under drained conditions, the dam yielded a FS of 1.61, a PF of 0% and a RI of 3.43 as shown in Figure 3a. The United States Army Corps of Engineers USACE (1997) classifies the expected dam performance into 7 categories which range from 'excellent' for a dam with a PF of 0% and a RI of 5 to 'hazardous' for a PF of 16% and an RI of 1 as shown in Table 4. Under drained conditions, the expected dam performance was therefore classified as 'above average'.

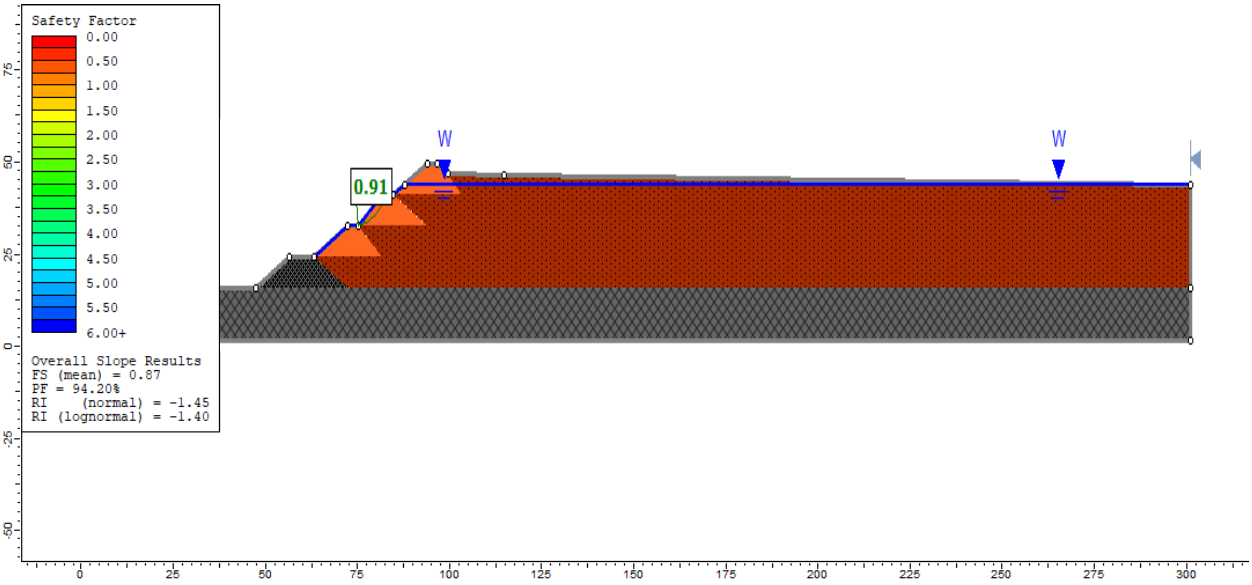
Table 4. *Expected dam performance classification (After USACE, 1997)*

Probability of failure (%	0.0	0.0	0.1	0.6	2.3	7.0	16.0
Reliability index	5.0	4.0	3.0	2.5	2.0	1.5	1.0
Expected performance	Excellent	Good	Above average	Below average	Poor	Unsatisfactory	Hazardous

The presence of groundwater can severely undermine the stability of tailings storage facilities. The buildup of seepage forces and pore water pressures reduces the tailings shear strength (τ) to the effective stress (τ'). When the strength loss is sufficiently high such that the destabilizing forces exceed the stabilizing forces, slope failure occurs. Under saturated conditions, the FS decreased to 0.91, the PF increased to 94% while the RI decreased to -1.45 as illustrated in Figure 3b. The Canadian Dam Authority (CDA) stipulates a permissible FS of 1.3 to account for uncertainties, which implies that the FS of 0.91 was unacceptably low. The analysis yielded a negative RI coupled with a high PF which positioned the dam in the hazardous category. It can also be observed in this case that the instability was caused by the porewater pressure buildup which led to loss of shear strength. Increasing the shear strength through reinforcement could potentially improve the dam stability and geogrids were used for that purpose.



a) Drained condition



b) Undrained condition

Figure 3. *Slope stability analysis of unreinforced tailings dam*

3.3 Slope stability analysis of geogrid reinforced tailings dam

When reinforcement is introduced, a second resisting moment M_G is applied to the conventional moment equilibrium. Figure 4 illustrates a typical model of a reinforced slope. The factor of safety is calculated by the expression:

$FS_R = (M_R+M_G/M_D) = (M_R +(T_{hor}Y))/M_D$
(1)
where, M_R = Resisting moment

M_G = Resisting moment due to reinforcement

M_D = Driving moment

T_{hor} = Horizontal tensile force of reinforcement

Y = Vertical distance between center of circle and reinforcement layer

The conservative approach assumes that the reinforcement tensile force acts horizontally, but the maximum value of resisting moment occurs when the reinforcement is inclined (T_{incl}). For multi-layered reinforcement, the resisting moment due to reinforcement is given by:

$M_G = \sum T_{incl} Y_i$
(2)

To provide adequate pullout resistance, the embedment reinforcement length (L_e) should extend beyond the critical slip surface. The following expression is used to calculate the embedment length:

$L_e = R_{po}FS/2C_i\sigma_n \tan\psi$
(3)

where R_{po} = Pullout resistance

C_i = Coefficient of interaction for pullout

σ_n =normal stress acting over geogrid anchorage length

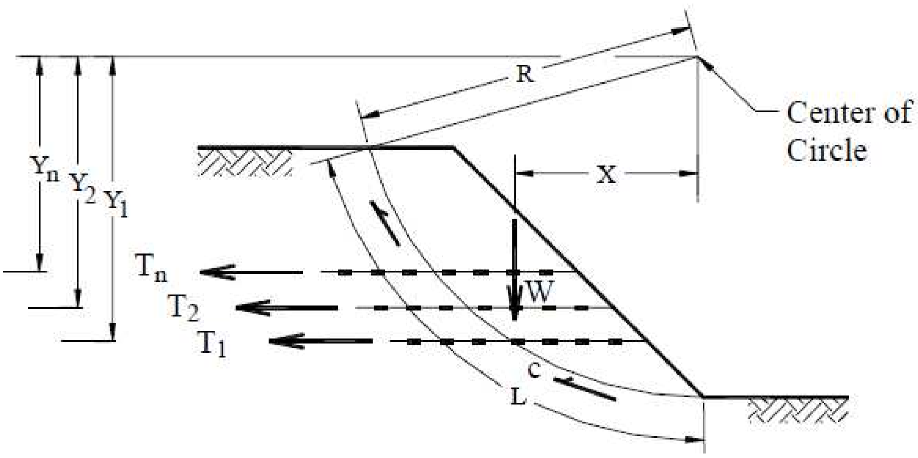


Figure 4. *Reinforced slope (Strata systems, 2010)*

For the tailings dam geogrid reinforcement design, the total length of each layer which included L_e (Equation 3) was 25m for the first dyke which was closest to the dam toe. For the upper dykes, the geogrid length was reduced to 20m and the geogrids were spaced at 1.8m. The slope stability analysis under drained conditions yielded a FS of 1.7, a PF of 0% and a RI of 6.2. At these values, the expected dam performance was categorized as 'high' in the USACE classification system. This demonstrated the capability of geogrids in improving the stability of upstream tailings dams. With geogrid reinforcement, the undrained tailings dam was in a more stable condition than the drained unreinforced tailings dam as shown by a higher FS and an increase of the RI by a factor of 1.8 from 3.4 to 6.2. In comparison with the undrained unreinforced facility, geogrid reinforcement improved the FS by a factor of 1.9 from 0.91 to 1.7, while the PF and RI had more than 100% improvement. Based on the results, it can be observed that geogrids can effectively stabilize tailings dams. Figure 5 presents the slope stability analysis of the geogrid reinforced tailings dam under saturated conditions.

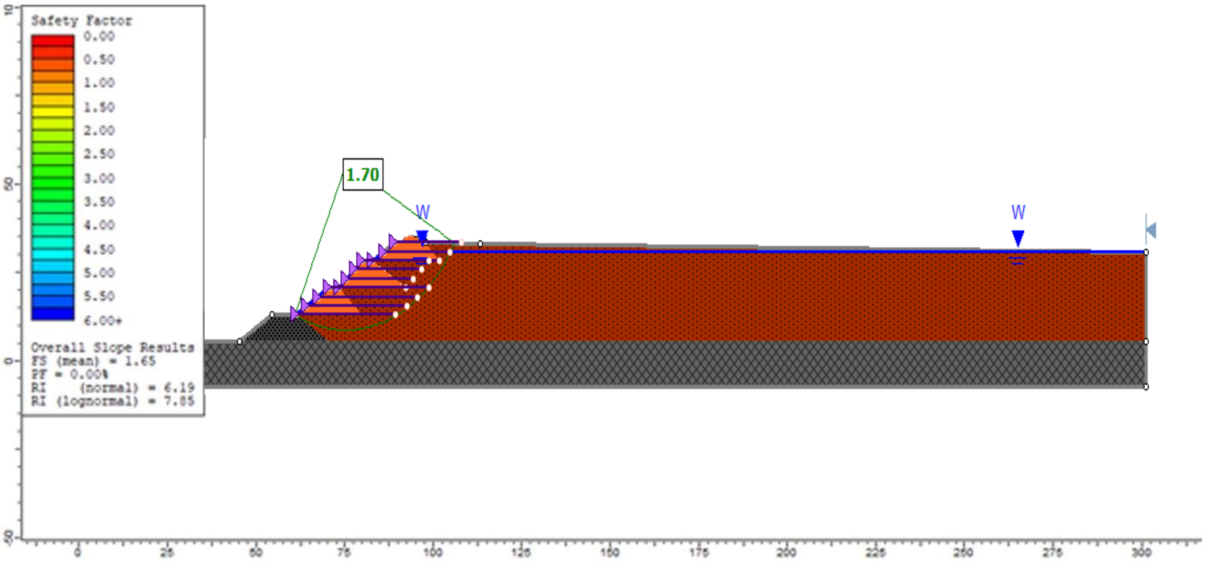


Figure 5. *Geogrid reinforced undrained tailings dam*

4 CONCLUSIONS

The failure of TSFs has become a global challenge which demands measures that can be used to effectively ensure the safe construction of the impoundments. While some regulators have responded to the crisis by denouncing the construction of upstream facilities, the geomechanics of tailings indicates that it is primarily the loss of shear strength and not the method of construction which leads to dam instability. Slope instability of TSFs can be addressed by implementing techniques which improve the tailings shear resistance. In this study, a geogrid reinforcement system was designed to stabilize a dam which had a high PF and low RI under saturated conditions. It was found that reinforcing the impoundment reduced the PF from 94% to 0% and increased the FS and RI to safe levels.

The efficiency of geogrid reinforcement will vary depending on the geogrid type and other factors which include the tailings geochemical and geotechnical characteristics and the dam geometry. Overall, the results demonstrated that reinforcing upstream tailings dams with geogrids improved their stability. The reinforcement of tailings dams using geogrids should be incorporated in routine TSF construction practices to enhance the safe disposal of mine waste. This is particularly critical in upstream impoundments which are more vulnerable to shear failure compared to other construction methods. The slope stabilization of TSFs with geogrids will minimize the risk of TSF failures and potential adverse consequences which include loss of human and animal life, infrastructural damage and environmental impacts; land, air and water contamination.

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