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Stability of Copper Mine Tailings Dam for Upstream, Downstream, and Centreline Construction Methods: Numerical Analysis

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ABSTRACT

Over the past few years, there have been numerous catastrophic tailings dam failures documented globally. In this study, the stability analysis of a copper mine tailings dam constructed by upstream (USM), downstream (DSM) and centreline (CSM) method was evaluated for static conditions by using finite element analysis. The developed numerical model was validated with the reported literature and it showed good agreement. The optimal combination between the height and slope of the tailings dam were investigated in terms of factor of safety and the failure planes were determined. The stability analysis was performed at each stage of construction of tailings dam. In order to enhance the stability of the tailings dam, several geogrid layers with varying vertical spacing between the layers were used. The optimum length of reinforcement was at a length to base width ratio of 1.3. Results revealed that the laying length and vertical spacing of the geogrid are the prime factors affecting the stability of tailings dam, whereas the stiffness of geogrid does not considerably affect the stability. It was also observed that the sequential construction of upstream method has high excess pore water pressure in comparison to other methods. The seismic resistance of the tailings dam was also evaluated. It was observed that the upstream method of construction was more susceptible to seismic conditions. The factor of safety decreased by about 15%, 13%, and 11% in the case of USM, DSM, and CSM, respectively, when horizontal seismic coefficient increased from 0.06g to 0.10g.

Keywords: Copper mine tailings, Slope stability, FEM, geogrid.

1 INTRODUCTION

Over the past decade, the demand for different mineral ores has drastically increased, leading to large-scale mining and processing of mineral ores. The extraction of beneficial components (metals) from these ores has led to the production of a large amount of mining waste called mine tailings. These mine tailings are primarily made up of fine-grained particles with high-water content and residual chemicals after metal extraction (Bussière, 2007; Martin & David, 2022). The global annual production of copper is estimated to be 20 million metric tonnes. It has been reported that for every tonne of copper ore mined, 0.96 t of copper mine tailings (CMT) are produced. Tailings dams are constructed for the storage of tailings in slurry form. It is estimated that there are about 3500 active tailings impoundments worldwide. Mount Polley dam (Canada), padcal mine, (Philippines), Aitik mine, (Sweden), Niujiaolong, (China) are some examples of copper mine tailings dam failures worldwide (Piciullo & Nungesser, 2022). The tailings dam can be classified as upstream, downstream, and centreline tailing dams based on the sequential raising technique. In the upstream method, the tailings are deposited on the crest of the initial starter dike, whereas in the downstream and centreline method, the tailings are discharged towards the back of the starter dike. In common practices, the upstream construction method is mostly utilized due to its cost-effectiveness and rapid construction, but it is not particularly stable in seismic conditions. It accounts for the highest number of dam failures.

Various researchers have investigated the stability of tailings dams in the past by calculating the factor of safety of the slope (Ormann et al., 2013; Wei et al., 2009; Yao et al., 2021). Psarropoulus and Tsomapanakis (2007) have conducted stability analysis on upstream, downstream, and centreline tailings dams, and reported that the raising height of the upstream method was less compared to the downstream and centreline method because dissipation of excess pore water pressure could not occur

in time. To further increase the stability of the mine tailing dam, numerous researchers have used geogrid reinforcement. Fazheng (2008) and Zuoan et al. (2014) successfully and effectively increased the safety and stability of mine-tailing reservoirs by installing high-strength geogrid in the dam body. Wei et al. (2009) used the reinforced terraced fields method with geogrids for the disposal of fine tailings and observed that the stability coefficient of the dams can be improved by 10–20%. Yishu et al. (2016) performed a model test on reinforced mine-tailing dams and demonstrated that the blockade effects associated with the deterioration process of reinforced belts could effectively increase the stability of dams. From the above discussion, it is evident that limited research has been carried out on the stability of copper mine tailings dams stabilized using reinforcement. Further, limited results are available on the influence of varying the reinforcement length, vertical spacing and stiffness of geogrids on the stability of tailings dam. In addition to this, the stability of tailings dam under seismic conditions are limited.
In the present study, the laboratory testing of the copper mine tailings was performed on the samples collected from the Malanjkhand copper deposit, Madhya Pradesh, India. In this mine tailings dam, upstream construction method is currently followed. The influence of length, spacing and stiffness of geogrid on the stability of copper mine tailings dam has been investigated. The numerical analysis for investigating the stability of mine tailings dam has been carried out using the finite element tool, Plaxis 2D, by employing upstream, downstream, and centreline methods of construction. Additionally, seismic analysis of the upstream, downstream, and centreline methods was carried out, and the safety factor was evaluated. It was noted that the upstream method is more economical, therefore, the height of the mine tailings dam was raised by applying geogrid reinforcement, and its stability analysis was performed.

2 METHODOLOGY

2.1 Material properties

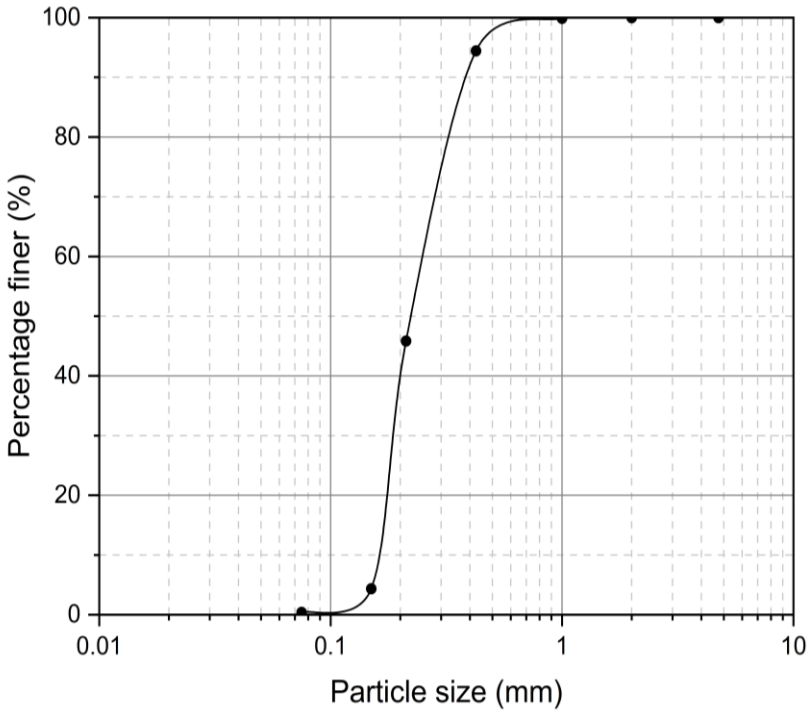

Figure 1 *Grain size distribution curve*

For the present study, the copper mine tailings specimen was collected at 1m depth in dry form from the Malanjkhand copper mine tailings dam located in Madhya Pradesh, India (22˚ 0'54''N and $80^0$43'20''E), which is an open-cast copper mine. A series of laboratory tests were performed to determine the geotechnical characteristics of the mine tailings, i.e., sieve analysis (refer Figure 1), standard proctor compaction test, constant head permeability, and direct shear test. The results of the laboratory tests are listed in Table 1. The properties of bedrock and clay were considered in line with the study of Xu and Wang (2015).

Table 1. *Material properties.*

Layer	Unit weight (kN/m^3)		Elastic constants			
	Dry unit weight	Saturated unit weight	E_{ref} (kN/m^2)	Poisson ratio	Cohesion Internal friction (kN/m^2)	Internal friction angle (°)
Granite[1]	25	25	12×10^6	0.22	1000	40.00
Clay[1]	17.1	19.5	7520	0.34	27.5	11.90
Tailings	15.6	17.5	2348	0.30	1	26.40
Intermediate tailings	15.6	17.6	3348	0.30	1	26.40

[1]Xu & Wang (2015)

2.2 Model validation

The numerical model used in the present study for slope stability analysis was validated for the upstream (USM), downstream (DSM), and centreline (CSM) methods. The geometry of the models is shown in Figure 2. The results of the analysis were found in line with the results of Psarropoulos and Tsompanakis (2007) and shown in tabular form in Table 2. A maximum deviation of about 5% was noted in the FOS values, which shows that the current numerical model is in good agreement and would be suitable to conduct further analyses. Figure 3 shows the values of FOS from the present study and the results reported by Psarropoulos and Tsompanakis (2007) for stage-wise construction of CSM.

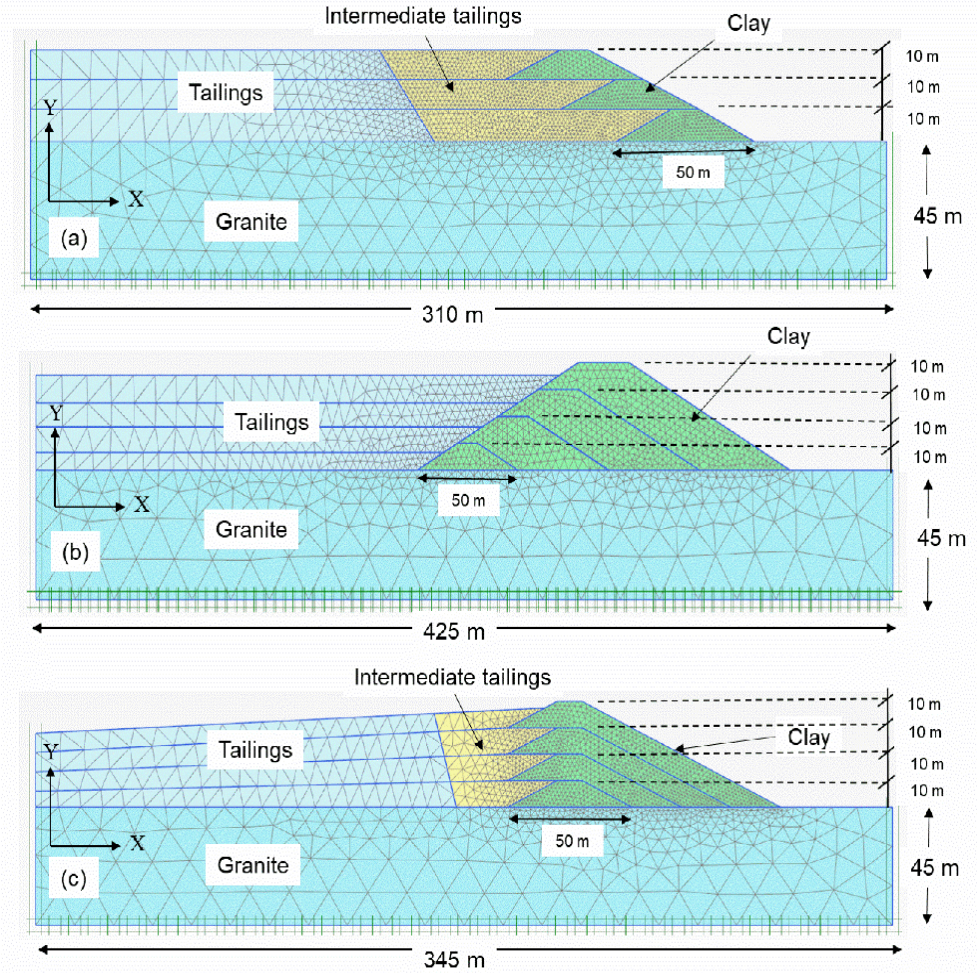

Figure 2 *Discretised mesh (a) upstream; (b) downstream; and (c) centreline method of construction.*

Table 2. *Validation of upstream, downstream, and centreline methods.*

Construction stage	USM			DSM			CSM		
	Reprt-ed study[2]	Present study	Error (%)	Report-ed study[2]	Present study	Error (%)	Report-ed study[2]	Present study	Error (%)
1	3.09	3.07	0.64	3.08	3.15	2.27	3.1	3.13	0.96
2	3.12	3.1	0.64	3.13	3.1	0.95	3.19	3.12	2.19
3	1.67	1.7	1.79	2.11	2.09	0.94	1.7	1.73	1.76
4	1.77	1.8	1.69	2.06	2.08	0.97	2.17	21.05	5.52
5	1.26	1.3	3.17	1.77	1.76	0.56	1.7	1.68	1.17
6	1.15	1.2	4.43	1.76	1.7	3.4	1.68	1.67	0.59
7	<1	<1	-	1.59	1.51	5.03	1.56	1.48	5.12
8	<1	<1	-	1.55	1.52	1.93	1.42	1.49	4.92

[2]Psarropoulos and Tsompanakis (2007)

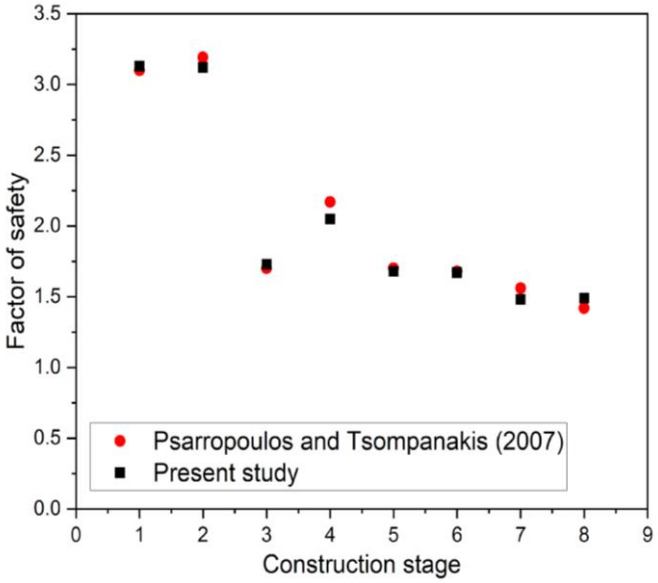

Figure 3 *Comparison of stage-wise FOS for CSM in the present study and Psarropoulos and Tsompanakis (2007)*

2.3 Numerical modelling

The stability of the copper mine tailings dam was analysed by using PLAXIS 2D, by employing the upstream, downstream, and centreline methods of construction. The horizontal extent of the bedrock was 580 m which was considered as per the study by Psarropoulos and Tsompanakis (2007). In the present study, various heights of the slopes were considered for different methods of construction. The height of the slope for upstream, centreline, and downstream methods were 30 m, 40 m, and 40 m, respectively. The phreatic line was assumed to be located just below the crest of the mine tailings.
The bottom horizontal boundary was restrained in both directions, whereas the vertical boundary was restrained in y- direction at both ends. The six-noded triangular elements were used in the present study to enhance the accuracy of the simulations and to reduce the computational time (Jaiswal et al., 2021). A higher number of elements were used in the vicinity of impending dam failure, resulting in a finer mesh in the embankment region. Mesh sensitivity analysis was carried out and medium mesh distribution with local refinement was used. The geometry for upstream, downstream and centreline methods of construction during the analysis is shown in Figure 4. The Mohr-Coulomb elasto-plastic constitutive model was used to simulate the behaviour of all the materials. The shear strength reduction technique was adopted for the safety analysis of the slopes. For the preliminary investigation, a single embankment was constructed in order to investigate the stability of the slope constructed using clay material. The details of the parametric study on the determination of suitable slope inclination from the horizontal are

shown in Table 3. It was noticed that the slope having inclination 1:4 (V:H) was suitable for the analysis of the aforementioned slope height.

Table 3. *Effect of slope inclination on the factor of safety.*

Case	Slope			
	Vertical V (m)	Horizontal H (m)	Inclination (V:H)	FOS
1	10	5	2:1	1.04
2	10	10	1:1	1.40
3	10	20	1:2	1.96
4	10	25	1:2.5	2.25
5	10	30	1:3	2.50
6	10	40	1:4	3.01

The geogrid reinforcement was modelled using a line element with axial elastic stiffness (*EA*) = 2000 kN/m and used to raise the height of the slope in the upstream method of construction. The axial elastic stiffness is calculated as the ratio of axial force per unit width to axial strain. The different methods of construction of the mine tailings dam were further investigated under seismic conditions because the dam site lies in active seismic zone III.

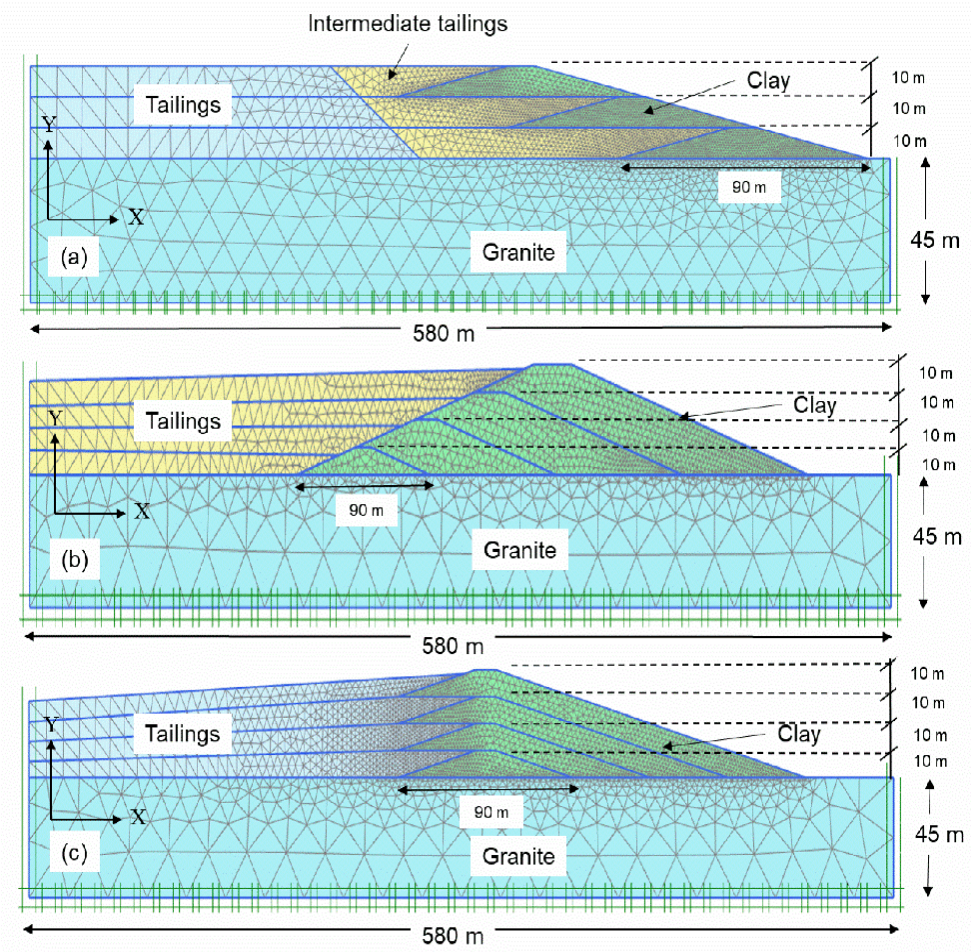

Figure 4 *Discretized mesh (a) upstream; (b) downstream; and (c) centreline method of construction*

3 RESULTS AND DISCUSSIONS

3.1 Stability of mine tailings dam using upstream, downstream, and centreline methods of construction.

After a preliminary investigation of the slope of the initial stage embankment, a 1:4 (vertical: horizontal) ratio of the slope was taken for further stages of construction in the upstream, downstream, and centreline methods. The upstream, downstream and centreline methods were constructed using Plaxis 2D. The stage-wise construction of the dam was considered and the raising of each stage was 10m. For the upstream construction method, 30 m raising was achieved in this study without geogrid. The upstream method is a fast and economical construction method. Due to rapid rate of raising, the excess pore water pressure increases and leads to a decrease in the strength and stability of the dam. The downstream and centreline methods are more stable because of their construction design and low raising rate of construction. This leads to a decrease in the development of excess pore water pressure and enhances the stability of the dam. In the present study, 40m height was achieved for the downstream and centreline method which is more than the upstream method. The dam crest is 10m for the upstream and downstream methods and 25m for the downstream method.

Table 4. *Factors of safety are calculated numerically at each stage of construction.*

	Factor of safety (FOS)			
Construction Stage	Upstream	Downstream	Centreline	IS: 7894 (1975)
1	2.99	4.48	3.01	> 1.3
2	2.97	4.41	3.00	> 1.3
3	2.05	2.86	1.99	> 1.3
4	2.03	2.85	1.98	> 1.3
5	1.84	2.33	1.65	> 1.3
6	1.83	2.31	1.64	> 1.3
7	1.12	2.05	1.48	> 1.3
8	<1	2.03	1.47	> 1.3

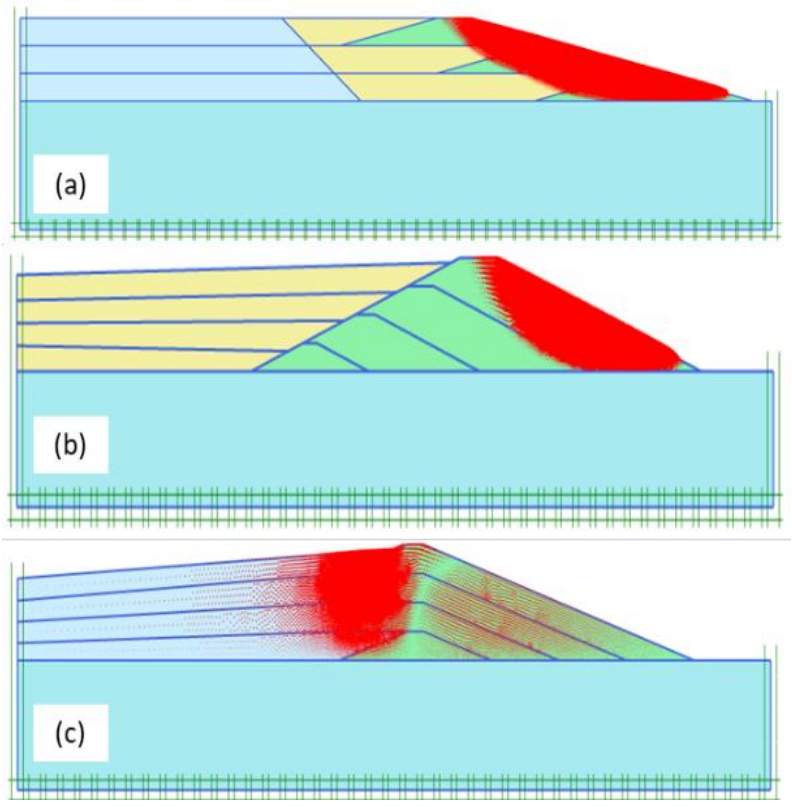

Figure 5 *failure mode plane (a) upstream; (b) downstream; and (c) centreline method of construction*

The safety factor was evaluated for each step of embankment construction during the numerical simulation of the models. The factor of safety values was compared with the recommended values in IS 7894 (1975) for every stage and method, and are shown in Table 4. It is evident that the factor of safety for tailings dam constructed by the upstream method is less than the recommended value (IS: 7894 (1975)) after its sixth stage of construction. The tailings dams constructed using the other two techniques (downstream and centreline) are in accordance with the recommended value of FOS during the construction phase. Figure 5 shows the most probable modes of failure for each of the analysed tailings dams. The upstream and downstream methods clearly showed the circular slip surface, while the centreline method does not show any circular slip surfaces because it is more stable than the other two methods.

3.2 Excess pore water pressure.

The excess pore water pressure is an important parameter for the assessment of stability of mine tailings dam during staged construction. This is because if sufficient time is not allowed for the dissipation of excess pore water pressure after each new construction phase, it may successively increase and affect the slope stability.

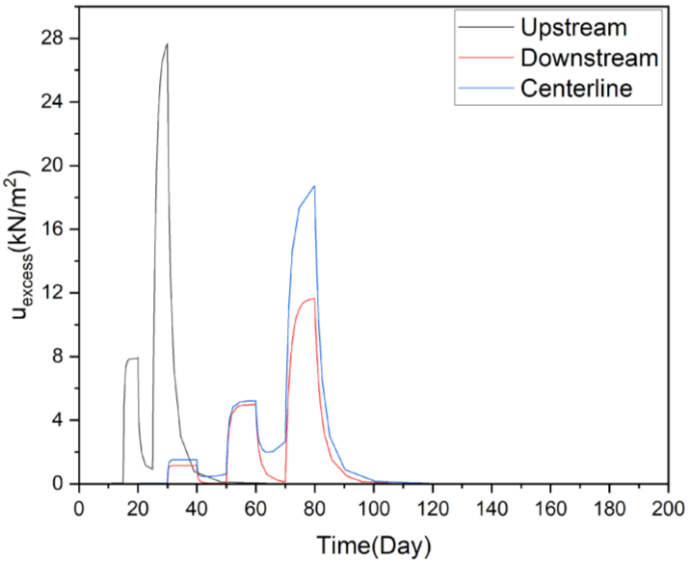

Figure 6 *Variation Excess pore water pressure with time in USM, DSM, CSM.*

Figure 6 shows the variation of excess pore water pressure for different dam construction methods. The raising rate of construction was high in the upstream method as compared to the downstream and centreline methods (Ormann et al., 2013). The rate of raising for the upstream method was taken as 5 days per stage. For downstream and centreline methods, the rate of raising was taken as 10 days per stage. Further, a time period of 200 days was allowed for the consolidation stage for all the cases. The maximum excess pore water pressure was observed under the upstream method because the construction time for upstream method was 15 days, which was less than the other two methods. These results are consistent with the findings of (Ormann et al., 2013). The fast construction does not allow the water to dissipate properly from the body of the dam and it leads to increase in the excess pore water pressure and significantly affects the stability of the dam.

3.3 Effect of length (L), vertical spacing (S_v), and elastic stiffness (EA) of geogrid on the FOS in upstream method.

The variation of FOS was studied by varying the length of geogrid (L), the vertical spacing between consecutive geogrid layers (S_v) and the elastic stiffness (EA) of the geogrid material and the results are shown in Tables 5 and 6. From the results, it can be observed that with the increase in L/b ratio, FOS increases for a particular S_v/h ratio. However, for a constant L/b ratio, S_v/h has minimal effect on the FOS. The effect of L/b ratio on FOS becomes insignificant for L/b>1.3, irrespective of the stiffness and S_v/h ratio. Therefore, it was concluded that the optimum length of reinforcement at ratio L/d=1.3.

Table 5. Variation of FOS for varying S_v/h and L/b at EA = 1000 kN/m

Ratio,(L/b)[3]	Ratio, (S_v/h)[4]					
	0.1	0.2	0.4	0.6	0.8	1
0.10	1.317	1.317	1.316	1.310	1.309	1.290
0.30	1.349	1.345	1.335	1.331	1.329	1.320
0.67	1.503	1.492	1.490	1.455	1.450	1.446
1	1.559	1.546	1.528	1.525	1.520	1.518
1.3	1.613	1.619	1.604	1.60	1.596	1.590
1.67	1.661	1.664	1.662	1.661	1.660	1.659

Table 6. Variation of FOS for varying S_v/h and L/b at EA = 2000 kN/m

Ratio,(L/b)	Ratio, (S_v/h)					
	0.1	0.2	0.4	0.6	0.8	1
0.10	1.318	1.317	1.318	1.313	1.310	1.307
0.30	1.359	1.356	1.338	1.337	1.335	1.324
0.67	1.519	1.495	1.494	1.458	1.456	1.455
1	1.569	1.554	1.554	1.534	1.534	1.528
1.3	1.630	1.628	1.628	1.616	1.616	1.604
1.67	1.653	1.665	1.665	1.662	1.661	1.660

[3]Ratio between geogrid length and base width of the embankment; [4]Ratio between geogrid spacing and dam height.

Also, from the results listed in Tables 5 and 6, it was also evident that the stiffness of reinforcement does not have much influence on the dam stability. The geogrid helps in improving the stability by providing anchorage to the failure zone of embankment.

3.4 Raising of the height of mine tailings dam using geogrid in the upstream method.

In the above discussions, it was noted that the slope was stable only up to a height of 30 m when constructed using the upstream method without geogrid. Therefore, geogrid reinforcement was used to further raise the height of the dam, without compromising its stability. Figure 7 shows the failure surface formed in the mine tailings dam reinforced with geogrids. It was noted that by inserting a geogrid at the base of the clay embankment at the interface of the second and third raise, the factor of safety of the dam increases. This occurs due to the fact that the stiffness of the clay material gets enhanced when reinforced with the geogrid because it forms a sandwiched material and the frictional resistance of the reinforcement tends to hold the soil in its original position. Therefore, the tailings dam was raised to a height of 40 m with the use of geogrids. The variation of the factor of safety during the construction stage is shown in Table 7.

Table 7. *FOS of mine tailing dam constructed using upstream method after reinforcement with geogrid.*

Factor of safety (FOS)		
Construction Stage	FOS (without geogrid)	FOS (with geogrid)
1	2.99	3.01
2	2.97	3.00
3	2.05	2.08
4	2.03	2.05
5	1.84	1.93
6	1.83	1.90
7	<1	1.65
8	<1	1.45

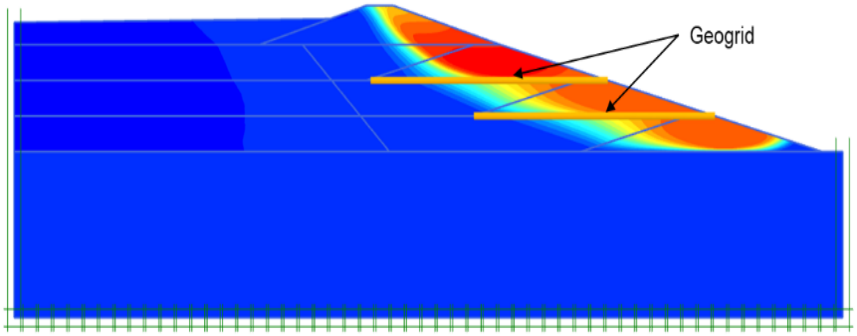

Figure 7 *Location of geogrid in the upstream method.*

3.5 Seismic analysis

In order to analyse the behaviour of the copper mine tailings dam in seismic conditions, a pseudo-static analysis was performed in the present study. The seismic loading was applied in the form of horizontal seismic acceleration coefficient (α_h) on the dams constructed using USM, DSM and CSM methods, and the outcomes are tabulated in Table 9. The results show that the FOS decreases with the increase in α_h, which can be attributed to the fact that ground shaking mobilizes the dam material, which further destabilizes the mine tailings dam. It was noticed that the FOS decreased by about 15%, 13%, and 11% in the case of USM, DSM, and CSM, respectively, when α_h increased from 0.06g to 0.10g. Furthermore, it was noted that the USM and CSM methods of construction cannot withstand the seismic loading of 0.20g. However, the DSM method of construction is safe at α_h = 0.20g. Therefore, it can be recommended that the performance of the DSM method of construction is better than USM and CSM methods for seismic loading. This is because the excess pore water pressure is lower in the DSM method as compared to the other two methods of construction and also construction design of DSM imparts resisting moment against seismic forces.

Table 8. Variation of FOS of dams constructed using various methods of construction under seismic loading

Case	Factor of safety			
	Horizontal seismic coefficient (α_h)	Upstream	Downstream	Centreline
Dam analyzed at H = 30m	0.00g	1.83	2.31	1.64
	0.06g	1.452	1.821	1.466
	0.10g	1.238	1.593	1.306
	0.20g	<1	1.197	<1
Dam analyzed at maximum height	0.00g	1.83	2.03	1.47
	0.06g	1.452	1.636	1.176
	0.10g	1.238	1.432	1.025
	0.20g	<1	1.077	<1

4 CONCLUSIONS

The present study aims to analyse the stability of a copper mine tailings dam under upstream, downstream, and centreline methods in static and seismic conditions using FEM. The preliminary part of the study was focused on the static stability analysis of major construction methods upstream, downstream, and centreline. The results revealed that the construction should be stage-wise and the height of raising in the upstream method is low when compared to the other two methods. The factor of safety values was obtained for the corresponding stages of construction and were also evaluated for different potential modes of failure. When comparing the FOS of the three models under consideration, it is clear that the FOS decreases with the advancement in the construction stages. The downstream method seems to be most stable for the construction of tailings dams for the stage-wise construction. The maximum height achieved in USM, DSM, and CSM were 30 m, 40m and 40 m, respectively. The excess pore water pressure was 29 kPa, 19 kPa, and 12 kPa for USM, DSM, and CSM, respectively. From the parametric study, it was observed that the influence of laying length is the most significant

parameter, while the stiffness of geogrid has a minimum effect on the stability of the copper mine tailings dam. The optimum length of reinforcement was found at a ratio of L/d=1.3. Moreover, the geogrid reinforcement was applied to raise the height of the upstream method from 30 m to 40 m. Furthermore, pseudo-static analysis was performed for seismic analyses of the copper mine tailings dam. The results revealed that the FOS decreased by about 15%, 13%, and 11% in the case of USM, DSM, and CSM, respectively, when α_h increased from 0.06g to 0.10g. The USM and CSM methods of construction cannot withstand the seismic loading of 0.20g. However, the DSM method of construction is safe at α_h = 0.20g. Therefore, it can be recommended that the performance of the DSM method of construction is better than USM and CSM methods for seismic conditions.

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