Parametric Study of Seismic Slope Stability of Tailings Dam

T. S. Aswathi(✉) and Ravi S. Jakka

Indian Institute of Technology, Roorkee, Uttarakhand 247667, India
as@eq.iitr.ac.in

Abstract. Tailings are the byproduct of the mining industry. The minerals mined by these mining industries are only about 3 to 5% pure, so the rest, 97 to 95%, become the tailings. It is being said that the increasing population has increased the demand for minerals for various uses. This demand produces a massive volume of tailings that, when disposed of inadequately, causes several failures and has cost lives in some cases. Therefore, a proper study of the design and safety of these structures is needed. This study aims to understand the stability variation of different tailings construction methods with different seismic loads. In this paper, the seismic slope stability of tailings dam is done by varying the slope angle of each dyke and material properties for three methods of construction – upstream, centerline, and downstream method of construction under different seismic loading. The numerical study is done in GeoStudio software.

Keywords: Seismic slope stability · Numerical analysis · Tailings dam

1 Introduction

In the mining industry, tailings are residue after extracting minerals from the mineral ore. In most cases, the mineral extracted is only 1 to 3% of the mineral ore; the rest is tailings deposited or pumped to a site nearby in a slurry form. Tailings contain water, rock fragments of varying sizes, metal (in trace quantities), and other chemicals used in ore processing. The most common disposing or distributing methods of tailings are subaqueous discharge, subaerial discharge, and thickened discharge. The cycloning principle separates the whole tailings slurry to coarse sand fraction called tailing sand and fine fraction with water called slimes. These slimes are impounded by the raised embankment of dyke using the tailing sand. These raised embankments are primarily built by the following three methods: upstream, downstream, or centerline. (Vick [11]). Among these three, the downstream method of construction is most stable. (Vick [11]; Psarropoulos and Tsompanakis [6] and Jakka [5]).

The literature has reported that there are 18000 tailings dams across the globe, out of which approximately 3500 are active. The primary difficulty in handling tailings dam is its instability during and after the mining operations. Before the year 2000, a total of 198 tailings dam failures were reported (Rio et al. [10]). Between the year 2000 - 2010 (Azam and Li [1]) and 2010 – 2021 (WISE [12]), a total of 20 and 36 tailings dam

L. Wang et al. (Eds.): PBD-IV 2022, GGEE 52, pp. 1914–1928, 2022.
https://doi.org/10.1007/978-3-031-11898-2_175

failure has been reported. The failure of the water retention dam (0.01%) is lower than the failure of the tailings dam (1.2%) (ICOLD [7]; Azam and Li [1]). The high failure rate of tailing dams has led to increasing awareness of the need for enhanced safety in the design and operation of tailing dams. Higher the tailings dam height higher the risk of failure (Klohn [8]; Azam and Li [1]; Davis [2]; Psarropoulos and Tsompanakis [6]; Ferdosi et al. [3, 4]).

In this paper, an attempt is made to study the effect of strength of foundation, tailings sand, and slimes on the factor of safety on three raised embankment types under static and dynamic conditions. The dynamic study is done by pseudo-static analysis considering that the tailings are constructed in India considering all four zones: zone 2, 3, 4 and 5. The parametric study is carried out with four different foundations, slimes, and tailings sand materials. Thus, Combination and permutation give a total of 64 cases. Each case is designated by nomenclature slime material - tailings material - foundation material. For example, S1_T1_F1 means that slime material is S1, tailings sand T1, and Foundation F1 is used in the case.

2 Methodology

This paper discusses the static and pseudo-static factors of safety of tailings dam constructed by upstream, downstream, and centerline methods. The geometry of these three tailings construction is shown in Fig. 1, 2, and 3. For this study, the construction of 3 types of the tailings dam is carried out with individual dyke of height 5 m, slope 4H:1V, and crest width 3 m to have a total height of 50 m. The analysis is carried out using GeoStudio software. The in-situ stresses are determined using an in-situ model of the QUAKE/W module. These results are then imported to the SLOPE/W module to find the static and pseudo-static factors of safety of the downstream side of the tailings dam in all three cases. The FEM static factor of safety (FOS_{static}) is carried out, and pseudo-static factor of safety (FOS_{ps}) is carried out by LEM Morgenstern – price method using effective stress parameters.

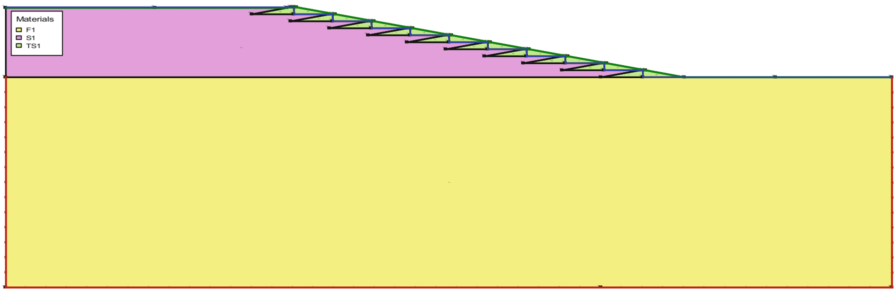

Fig. 1. The geometry of upstream method of construction with drainage condition

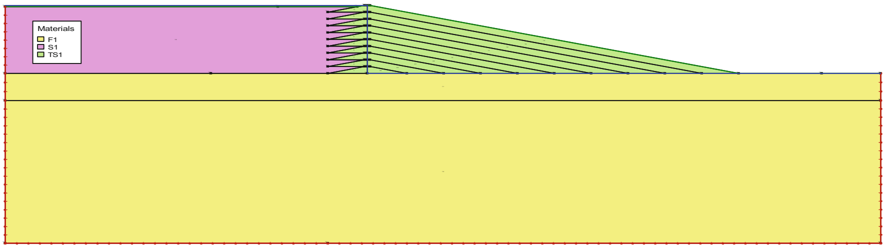

Fig. 2. The geometry of centerline method of construction with drainage condition

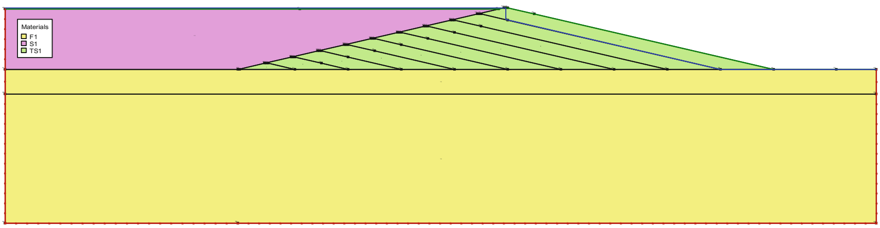

Fig. 3. The geometry of downstream method of construction with drainage condition

For the parametric study, the material properties are taken as Table 1 and pseudo-static coefficient as Table 2. Four sets of values are considered for the material properties of tailings sand (T1, T2, T3, T4), slimes (S1, S2, S3, S4), and foundation (F1, F2, F3, F4). Therefore, there are 64 cases for each tailings dam type. The horizontal seismic coefficient is calculated per IITKGSDMA [9] by considering the importance factor, I, as 1.5; site amplification factor S1 for foundations F1, F2, and F4 whereas S2 for foundation F3. The vertical seismic coefficient is neglected as its effect on the factor of safety is negligible.

Table 1. Material properties considered in the analysis

Material	Material model	Unit weight $\gamma\left({kN}/{m^3}\right)$	Cohesion c' (kPa)	Frictional angle (°)	Poisson's ratio
F1	MC	21	0	40	0.28
F2	MC	19	0	35	0.3
F3	MC	17	0	30	0.3
F4	Bedrock – LE	24			0.2
S1	MC	13	0	29	0.33
S2	MC	14	0	31	0.33
S3	MC	15	0	33	0.33
S4	MC	16	0	35	0.33
T1	MC	16.5	0	33	0.3
T2	MC	17.5	0	35	0.3
T3	MC	18.5	0	37	0.3
T4	MC	19.5	0	39	0.3

* MC – Mohr-Coulomb and LE – Linearly Elastic

Table 2. Horizontal seismic coefficient

Zone	Zone factor, Z	Site amplification factor		Importance factor, I	Horizontal seismic coefficient α_H considering site factor	
		S1	S2		S1	S2
2	0.1g	1	2	1.5	0.05g	0.1g
3	0.16g	1	1.5	1.5	0.08g	0.12g
4	0.24g	1	1.2	1.5	0.12g	0.144g
5	0.36g	1	1.0	1.5	0.18g	0.18g

3 Result and Discussion

3.1 Effect of Foundation

To study the effect of foundation on the factor of safety of tailings dam, the cases with constant tailings sand for dyke and slimes are considered. In this study, the order of strength of foundation considered is F4 > F1 > F2 > F3. The FOS_{static} and FOS_{ps} follows the order of strength of the foundation in all the three cases names upstream, centerline, and downstream methods of construction of the tailings dam. The variation of FOS_{ps} is shown in Fig. 4, 5, and 6 for the upstream, centerline, and downstream tailings method in zone 2. Similar charts are also drawn for static and other pseudo-static cases.

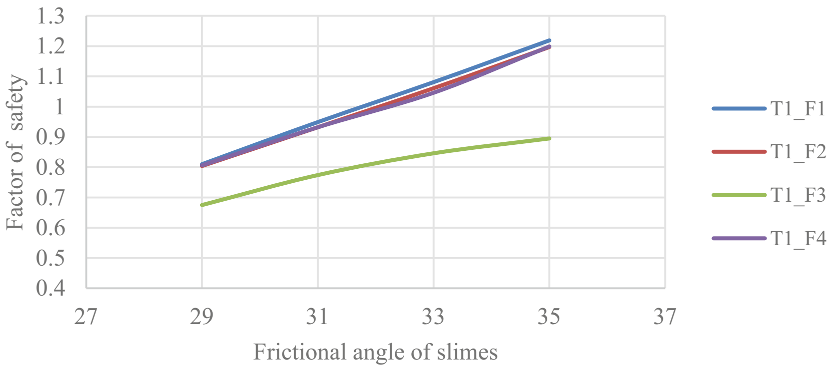

Fig. 4. The factor of safety of upstream tailings dam with constant tailings in zone 2

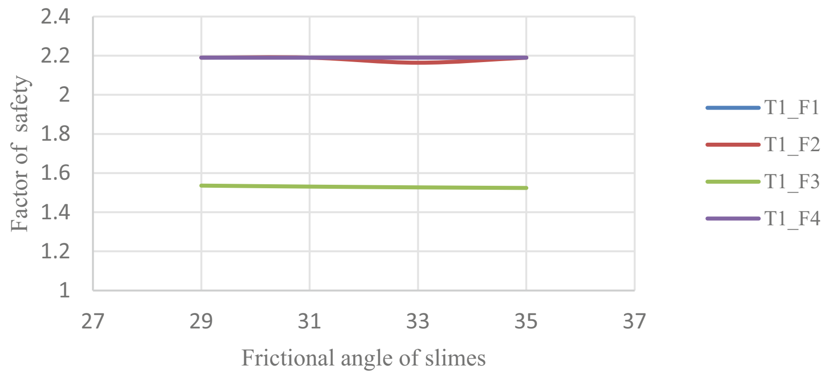

Fig. 5. The factor of safety of centerline tailings dam with constant tailings in zone 2

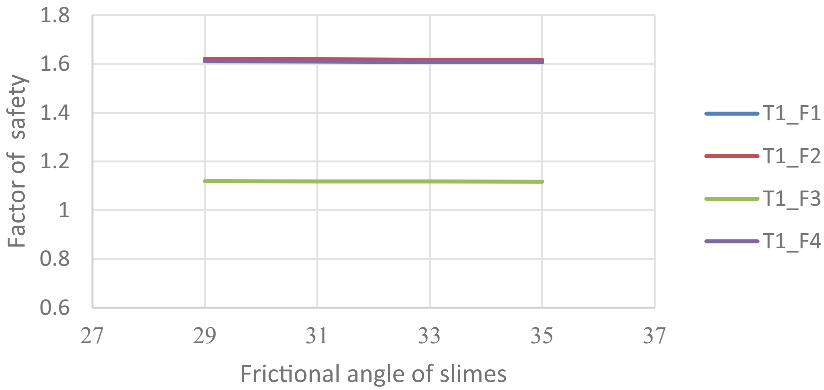

Fig. 6. The factor of safety of downstream tailings dam with constant tailings in zone 2

The slip surface changes from the shallow slope failure for F4, F1, and F2 to a deep base failure for F3, as shown in Figs. 8 and 9 in the case of centerline and downstream construction methods. However, there is not much change in slip surface in the case upstream method of construction constructed on the different foundation (Fig. 7).

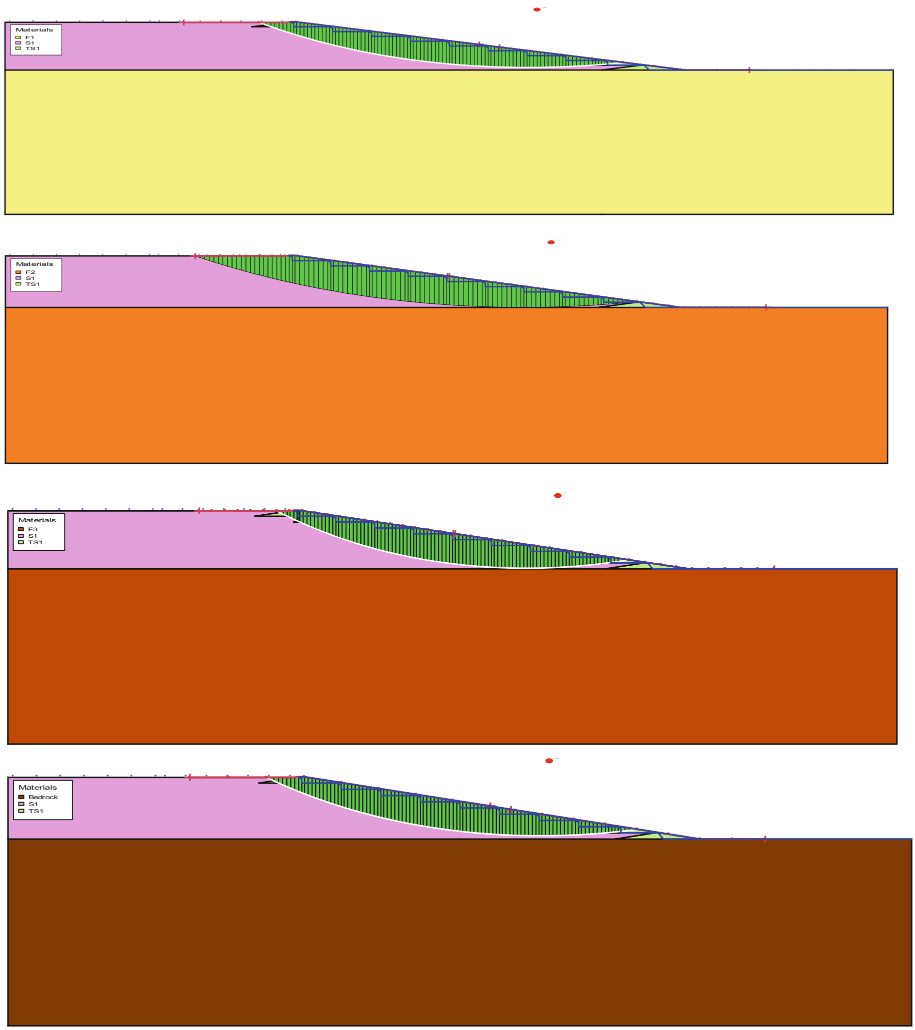

Fig. 7. Slip surface of upstream tailings under static analysis having different foundations F1, F2, F3, and F4 in order. (The results shown are for the cases S1_T1_F1, S1_T1_F2, S1_T1_F3, S1_T1_F4)

3.2 Effect of Tailings

To study the effect of tailings on the factor of safety of the tailings dam, cases with constant foundation and slimes are analyzed, and the results are plotted (Fig. 10, 11, and 12) for pseudo-static analysis in zone 2 of upstream, centerline, and downstream tailings on Foundation F1. Similar graphs are drawn from the rest of the sets. Therefore, the factor of safety is in the order of strength of the tailings for all the three types: upstream,

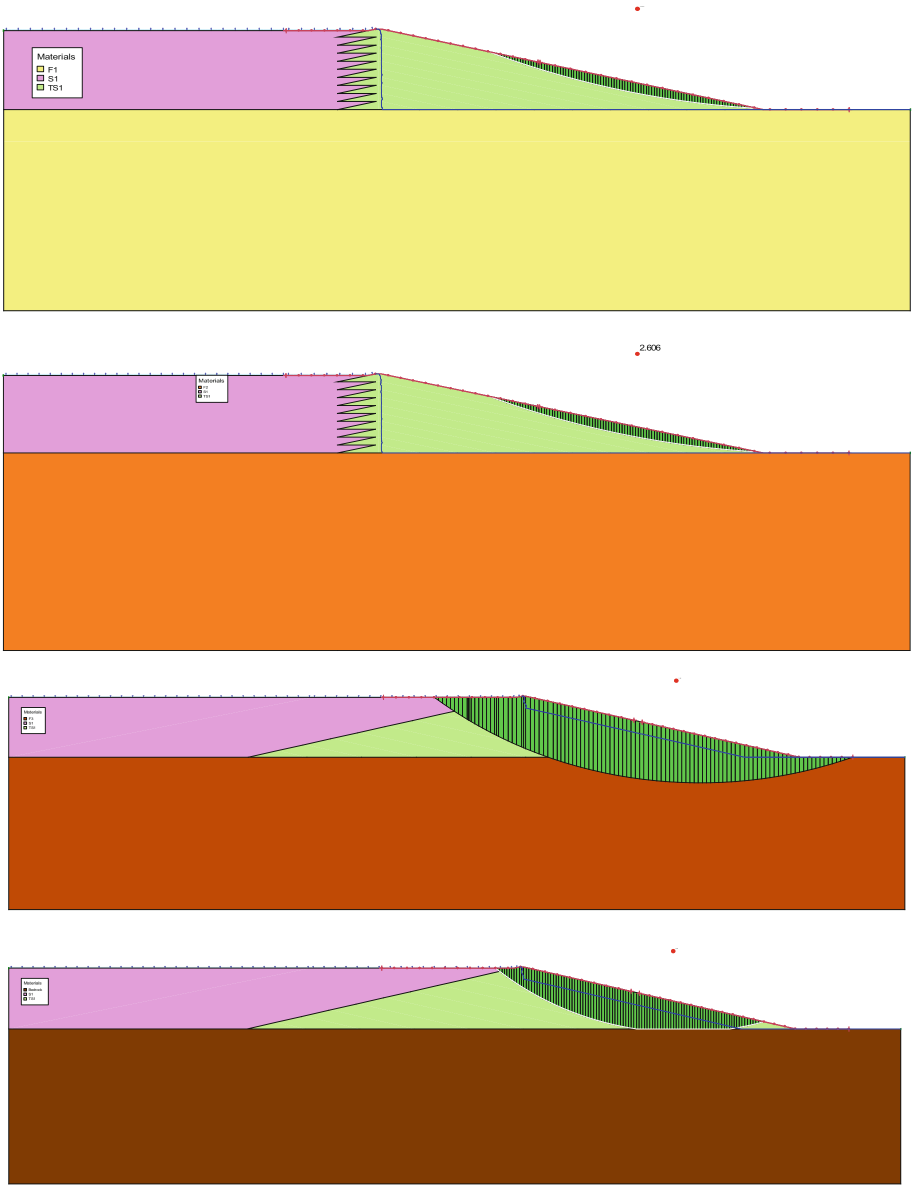

Fig. 8. Slip surface of centerline tailings under static analysis having different foundations F1, F2, F3, and F4 in order. (The results shown are for the cases S1_T1_F1, S1_T1_F2, S1_T1_F3, S1_T1_F4)

downstream, and centerline for both static and pseudo-static cases. The critical slip surface shape remains the same for the same foundation combination cases (Fig. 13).

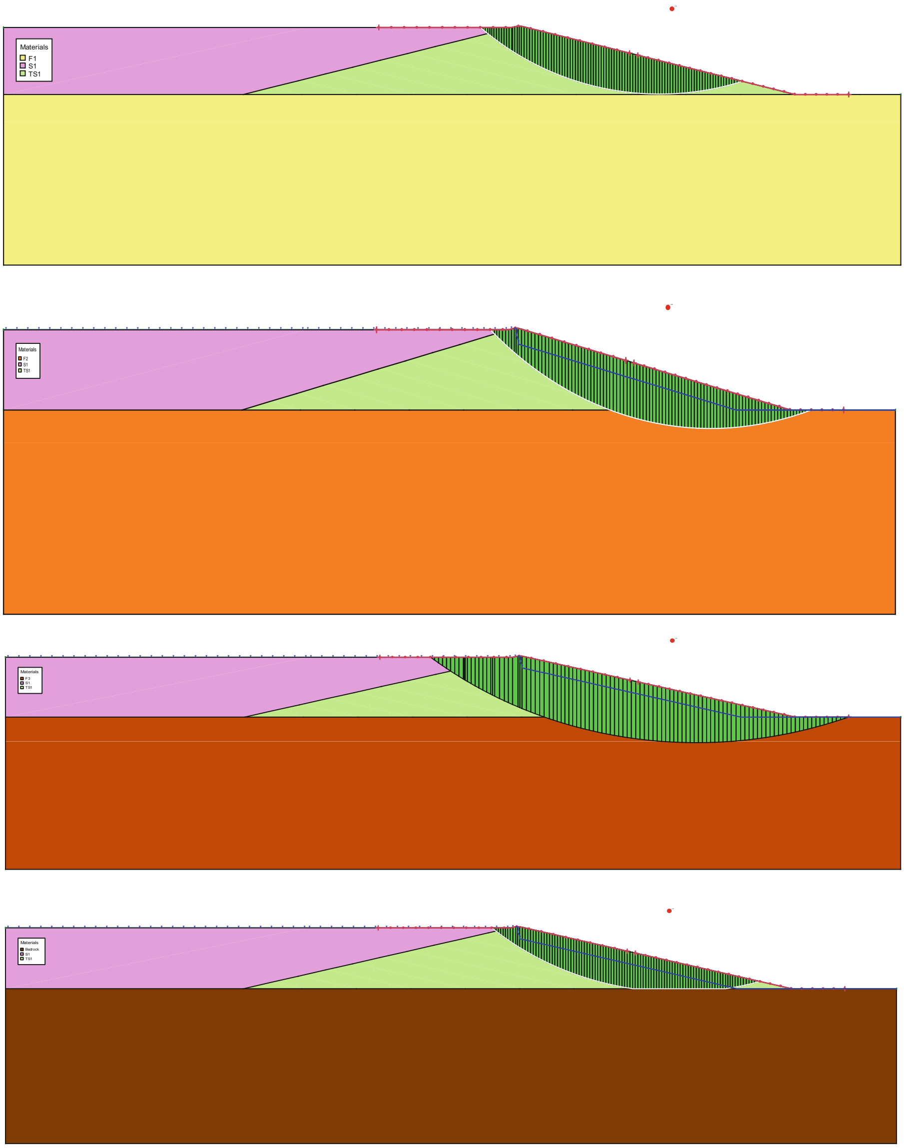

Fig. 9. Slip surface of downstream tailings under static analysis having different foundations F1, F2, F3, and F4 in order. (The results shown are for the cases S1_T1_F1, S1_T1_F2, S1_T1_F3, S1_T1_F4)

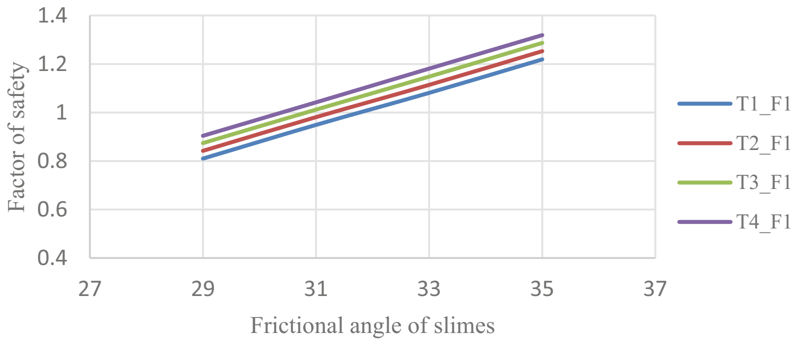

Fig. 10. The factor of safety upstream tailings dam with the constant foundation in zone 2

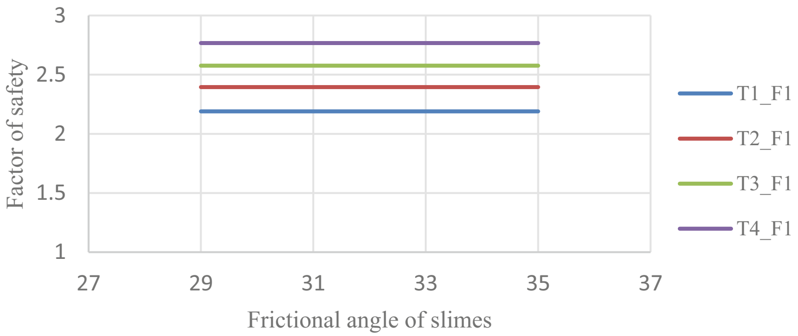

Fig. 11. The factor of safety centerline tailings dam with the constant foundation in zone 2

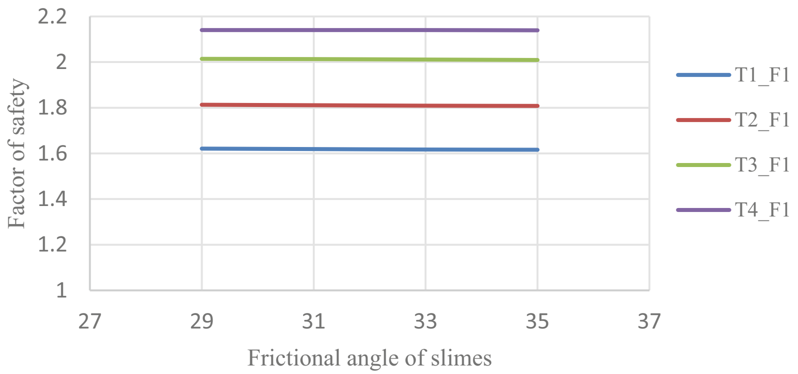

Fig. 12. The factor of safety downstream tailings dam with the constant foundation in zone 2

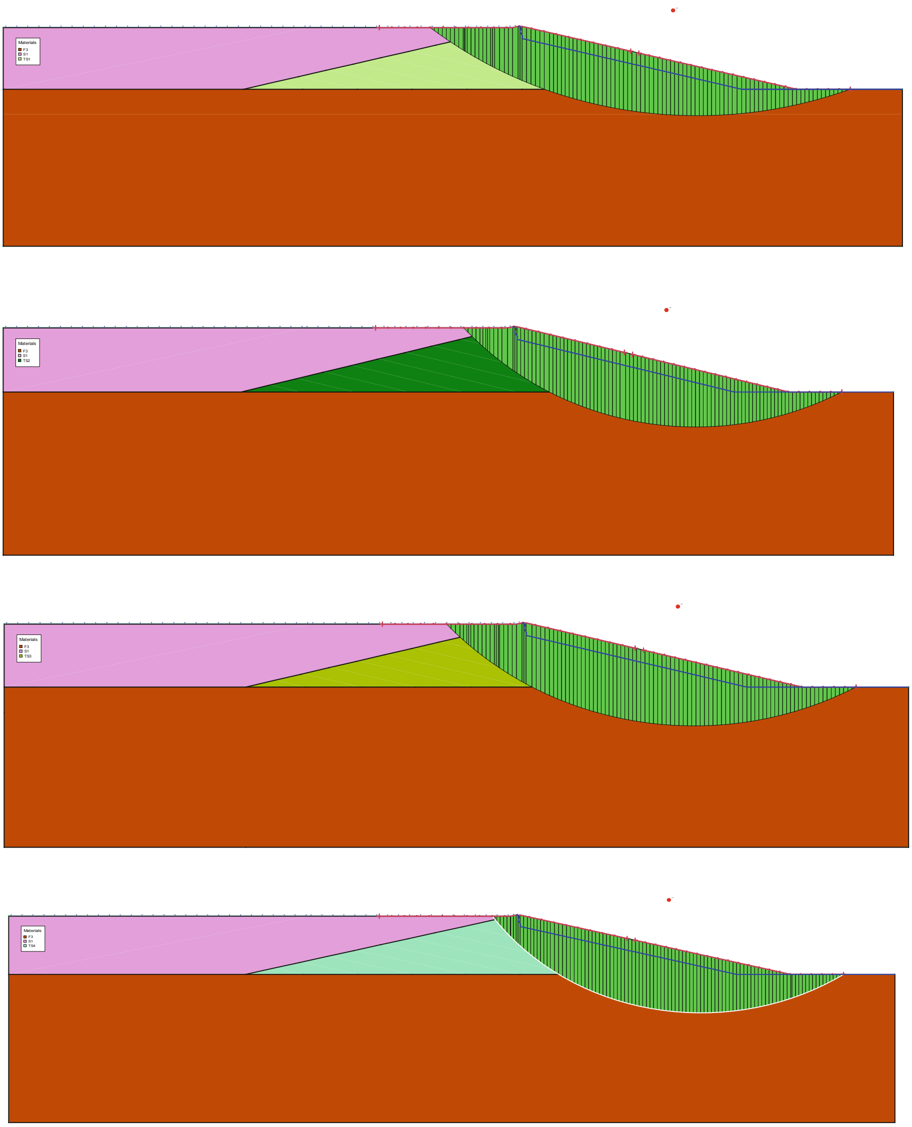

Fig. 13. Slip surface of downstream tailings under static analysis having different tailings sand TS1, TS2, TS3, and TS4 in order. (The results shown are for the cases S1_T1_F3, S1_T2_F3, S1_T3_F3, S1_T4_F4)

3.3 Effect of Slimes

To study the effect of slimes on the factor of safety of tailings dam, cases are grouped having the same foundation and tailings sand for dyke, and graphs are plotted for the factor of safety variation with frictional angle of slimes. Figure 14 shows that the factor of safety increases as the angle of slimes increases in the case of upstream for pseudo-static in zone 2. In the case of downstream, the factor of safety remains constant with the increase in the frictional angle of slimes (Fig. 16). Furthermore, for the centerline method, the factor of safety decreases with the increased frictional angle of slimes (Fig. 15). The same is true for static and other pseudo-static cases in the respective tailings dam type. The critical slip surface remains the same shape (Fig. 17).

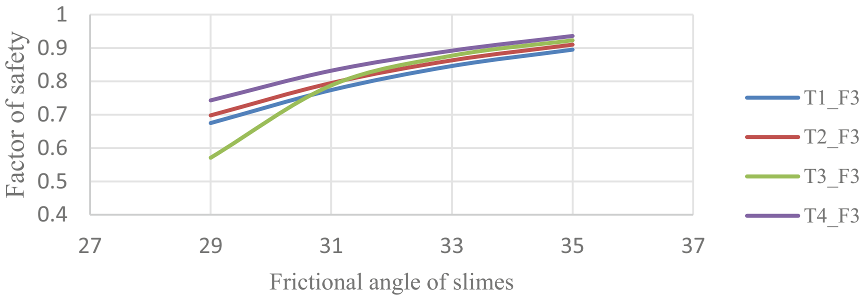

Fig. 14. The factor of safety upstream tailings dam with the constant foundation in zone 2

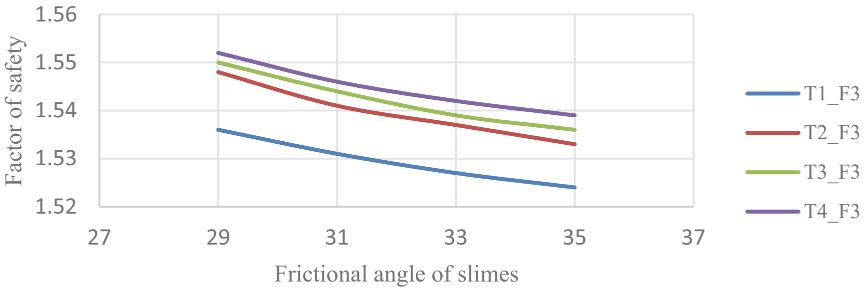

Fig. 15. The factor of safety centerline tailings dam with the constant foundation in zone 2

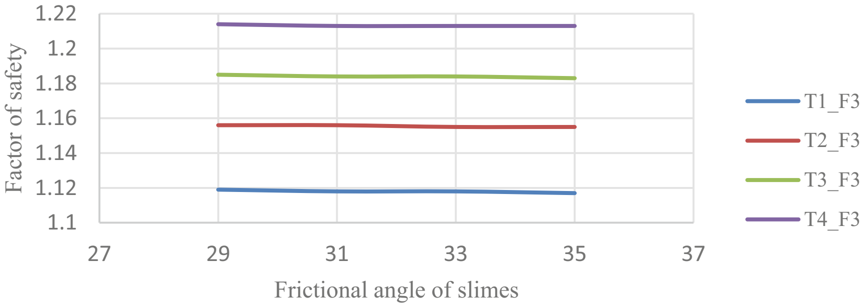

Fig. 16. The factor of safety downstream tailings dam with the constant foundation in zone 2

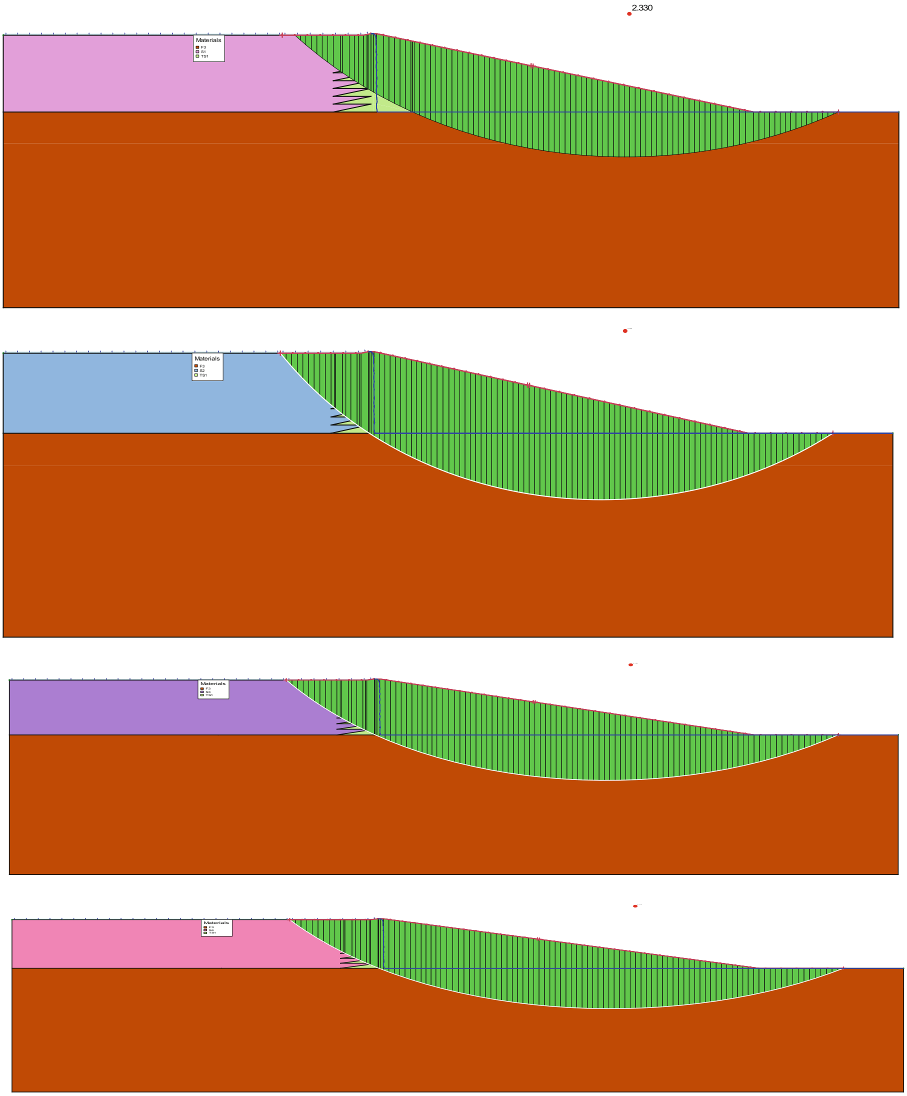

Fig. 17. Slip surface of centerline tailings under static analysis having different slimes S1, S2, S3, and S4 in order. (The results shown are for the cases S1_T1_F3, S2_T1_F3, S3_T1_F3, S4_T1_F3)

3.4 Construction Method

Comparing factors of safety between the three methods of construction, Fig. 21, it can be said that the centerline method is the safest and upstream method least safe for both static and pseudo-static cases. This difference in the order that the centerline method has more safety than downstream is because of the drainage condition considered in this study. Usually, the downstream method gets inclined drainage towards the upstream side of the dyke. The upstream tailings dam is unsafe, especially in the active seismic area. From Fig. 18, 19 and 20, it can be said that the factor of safety decreases with an increase in seismic loading, and the trend of the safety remains the same with respect to the slimes, tailings sand, and foundation combination.

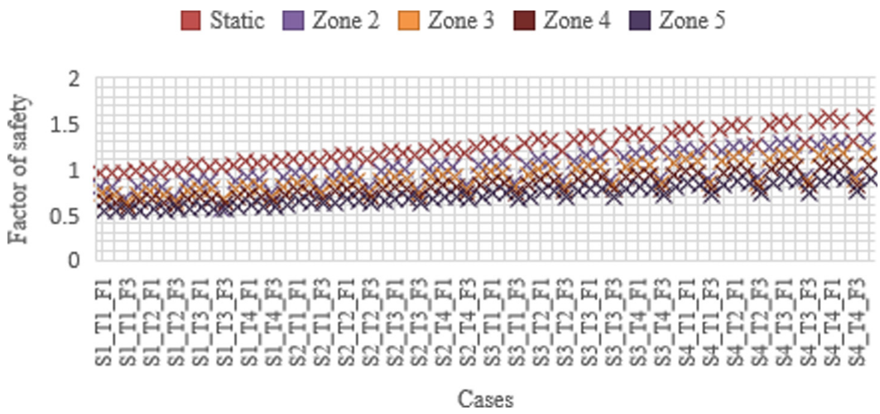

Fig. 18. Variation of the factor of safety for static and pseudo-static cases for zone 2, 3, 4, and 5 for upstream tailings dam for 64 cases.

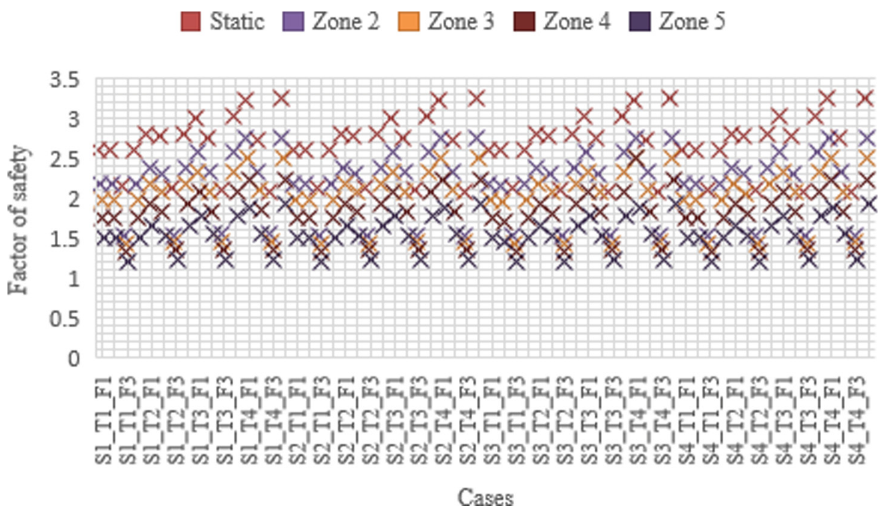

Fig. 19. Variation of the factor of safety for static and pseudo-static cases for zone 2, 3, 4, and 5 for centerline tailings dam for 64 cases.

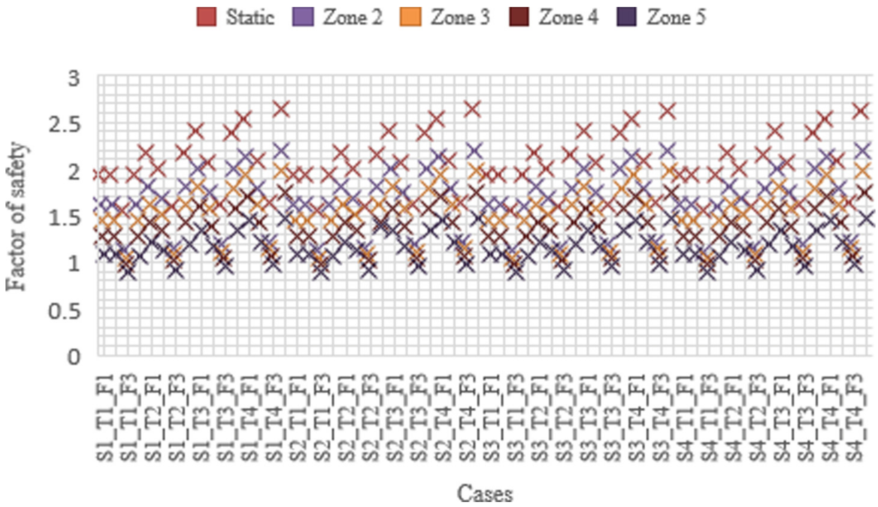

Fig. 20. Variation of the factor of safety for static and pseudo-static cases for zone 2, 3, 4, and 5 for downstream tailings dam for 64 cases.

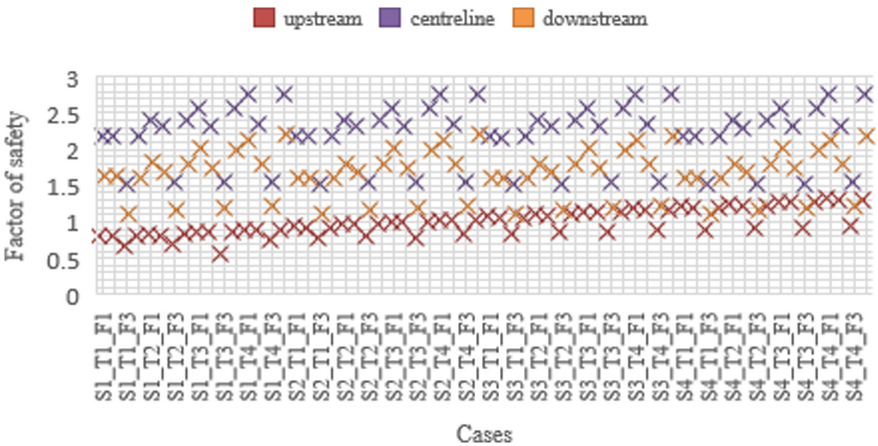

Fig. 21. Variation of the factor of safety for pseudo-static zone 2 for upstream, centerline, and downstream tailings dam for 64 cases.

4 Conclusions

In this paper, a parametric study is carried out with four sets of material properties for foundation, tailings sand, and slimes (64 cases) for three raised embankment construction methods, namely upstream, downstream, and centerline methods of construction with the same dike geometry for constructing a total height of 50 m height tailings dam. The following conclusions are drawn. The upstream method is the most unsafe construction in seismic conditions. According to this study, the centerline construction method is most stable, but this is due to the drainage condition considered in downstream construction.

The foundation effect is linear and more profound, followed by tailings sand and finally slimes. The effect of slimes has a nonlinear relationship to safety in the upstream and centerline construction method. However, there is no effect of slimes in downstream tailings. The factor of safety decreases with the increase in seismic loading irrespective of the tailings type.

References

1. Azam, S., Li, Q.: Tailings dam failures: a review of the last one hundred years. Geotech. News **28**(4), 50–54 (2010)
2. Davies, M.P.: Tailing's impoundment failures Are geotechnical engineers listening? Geotech. News-Vancouver **20**(3), 31–36 (2002)
3. Ferdosi, B., James, M., Aubertin, M.: Investigation of the effect of waste rock inclusions configuration on the seismic performance of a tailings impoundment. Geotech. Geol. Eng. **33**(6), 1519–1537 (2015)
4. Ferdosi, B., James, M., Aubertin, M.: Numerical simulations of seismic and post-seismic behavior of tailings. Can. Geotech. J. **53**(1), 85–92 (2015)
5. Jakka, R.S., Ramana, G.V., Datta, M.: Seismic slope stability of embankments constructed with pond ash. Geotech. Geol. Eng. **29**(5), 821–835 (2011)
6. Psarropoulos, P.N., Tsompanakis, Y.: Stability of tailings dams under static and seismic loading. Can. Geotech. J. **45**(5), 663–675 (2008)
7. ICOLD U. Tailings dams–risk of dangerous occurrences, lessons learnt from practical experiences (bulletin 121). Commission Internationale des Grands Barrages, Paris (2001)
8. Klohn, E.J.: Tailings dams in Canada. Geotechnical News 117-23 (1997)
9. Roy, D., Dayal, U., Jain, S.K.: IITKGSDMA guidelines for seismic design of earth dams and embankments, provisions with commentary and explanatory examples. Indian Institute of Technology Kanpur (2007)
10. Rico, M., Benito, G., Salgueiro, A.R., Díez-Herrero, A., Pereira, H.G.: Reported tailings dam failures: a review of the European incidents in the worldwide context. J. Hazard. Mater. **152**(2), 846–852 (2008)
11. Vick, S.G.: Planning, Design, and Analysis of Tailings Dams. Wiley, New York (1983)
12. WISE (World Information Service on Energy Uranium Project). Chronology of major tailings dam failures. https://www.wise-uranium.org/mdaf.html. Accessed 16 Dec 2021