Proceedings of the 8th World Congress on Civil, Structural, and Environmental Engineering (CSEE'23)
Lisbon, Portugal – March 29 – 31, 2023
Paper No. ICGRE 122
DOI: 10.11159/icgre23.122

Numerical Investigation on Tailing Dams Stability: a Preliminary, Parametric Analysis of some Key Factors

Gianluca Bella[1], Carolina Freire[2], Fernando Lameiras[2], Matteo Giani [1-3]
[1] Pini Group Ltd
Via Besso 7, Lugano, Switzerland
[2] Centro de Desenvolvimento da Tecnologia Nuclear
Avenida Presidente Antônio Carlos 6627, Belo Horizonte, Brasil
[3] Scuola Universitaria Professionale Svizzera Italiana (SUPSI)
Via Flora Ruchat-Roncati 15, Mendrisio, Switzerland
gianluca.bella@pini.group, cbf@cdtn.br, fsl@cdtn.br, matteo.giani@pini.group

Abstract **-** Tailing wastes are by-products of mining industry and are generally mixtures of rock, sand, fine-grained solid material and in some cases relevant quantities of heavy metals and water remaining after the mineral values have been extracted from the patent ore. In recent years the amount of tailings has significantly increased to meet the growing demand for metals and minerals. Huge amounts of tailing wastes are produced and discharged inside storage facilities (TSF), also known as tailing dams. Owing to their complexity and high rate of collapses with relevant loss of human lives, economic and environmental damages, a detailed knowledge of the hydro-mechanical properties of tailings is essential to develop a reliable stability analysis both for new and existing structures. This research provides a preliminary parametric study aimed at investigating the impact of some fundamental design aspects. The influence of the adopted numerical method, raising techniques, distance of decant pond, hydraulic conditions, geometry of drainage systems and uncertainty of geotechnical properties on stability of an embankment have been evaluated for a simple case, providing some fundamental concepts to be considered when designing new tailing dams or performing stability analysis on existing ones.

***Keywords*:** tailings; stability analysis; tailing dams; safety factor; Finite Element Method; Limit Equilibrium Method.

1. Introduction

Tailings are the waste materials resulting from mining activities, and consist of mixtures of crushed rocks, chemicals, water, and processing fluids with a particle size ranging from sand to clay/silt size. Tailing dams represent some of the man-made, largest, and complex geotechnical structures in the world. They consist of an earth embankment raised by stages over the life of the impoundment, and a basin to store billions of tons of tailing materials as shown in Fig. 1 ([1]-[2]).

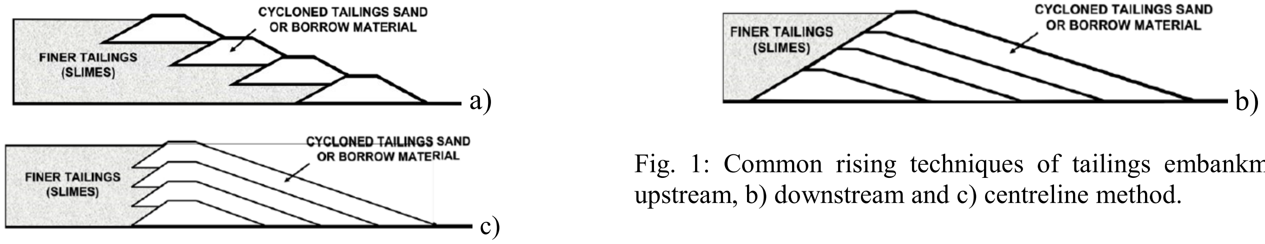
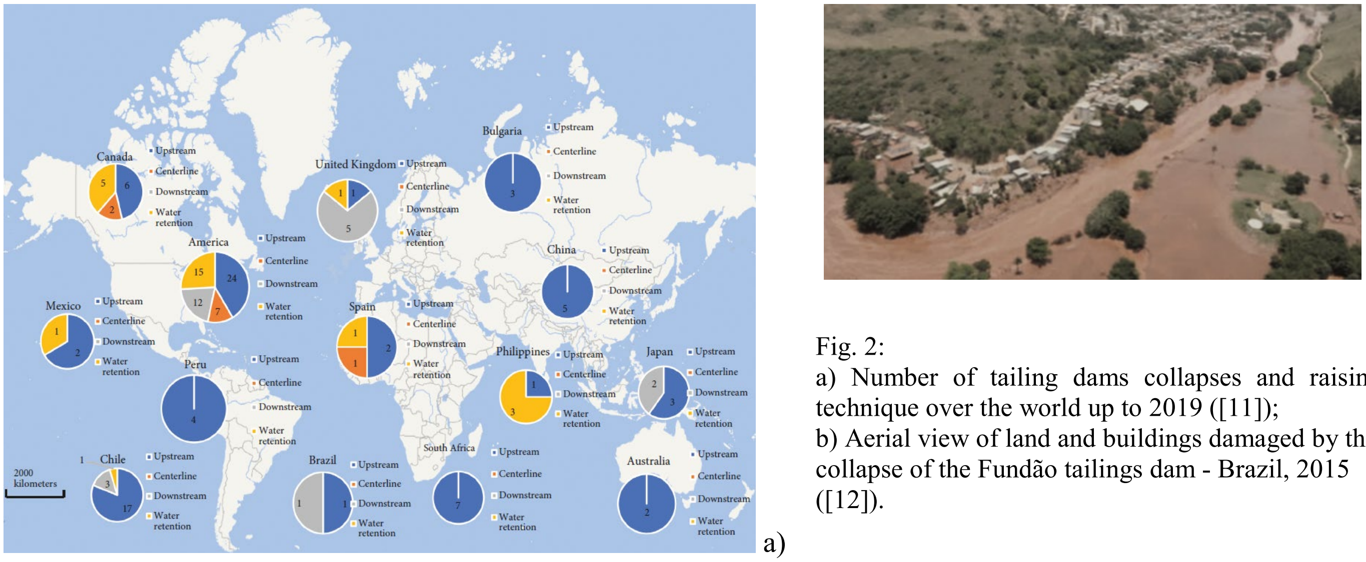


Fig. 1: Common rising techniques of tailings embankment: a) upstream, b) downstream and c) centreline method.

Due to the deposition techniques and other factors (i.e., spatial extension and long operation life), tailings deposited within storage facilities are heterogeneous, both in terms of grain size distribution and density. Furthermore, tailing basins are subjected to many external actions and phenomena affecting their operation, i.e., surface runoff, infiltration and consolidation process, capillary rise or chemical reactions that generate additional products, such as acids, that can more easily leach into waterways. Failures of such structures can have deleterious consequences on the environmental, society and even impact areas miles away far from the collapsed dam ([3]-[4]-[5]-[6]-[7]) as proved from the high rate of recent collapses in several countries (Fig. 2a). For these reasons, according to ([8]), mining wastes must be stored in a permanent and safe way, ensuring the stability of tailing impoundments guaranteed for more than 1000 years. There are many common failure modes to which tailing dams may be vulnerable, each one could lead to complete or partial embankment collapse. According to [9] and [10], about 25% of collapses worldwide are due to the meteorological causes usually associated to the static liquefaction phenomena: intense rainfall, hurricanes, rapid snowmelt, or ice accumulation inside tailing dam. The second cause of worldwide incidents is due to poor management, such as rapid dam growth, poor beach management or faulty maintenance of the drainage structures. Finally, the third cause of dam failures is associated to wrong design choices, while other common causes are associated to seepage/piping, overtopping and dynamic liquefaction. If a tailing dam collapses, a huge volume of stored tailings will flow as a viscous liquid, travelling large distances with severe consequences such as loss of human life, economic damages, and environmental pollution (Fig. 2b).



a)

b)

Fig. 2:
a) Number of tailing dams collapses and raising technique over the world up to 2019 ([11]);
b) Aerial view of land and buildings damaged by the collapse of the Fundão tailings dam - Brazil, 2015 ([12]).

The current study is aimed at analysing the stability of a hypothetic embankment by considering relevant factors that influence its safety level. Simplified stability analyses have been carried out by considering the influence of numerical approach, geometry of drainage systems, raising method, distance of the decant pond from the embankment and geotechnical properties of deposited tailings on the safety factor. The models were simplified for easy comparison between the three constructive methods and factors that are supposedly affecting the overall stability of the embankment.

.

2. Case Study: numerical models and analysis

Stability analysis for different raising techniques have been carried out by considering simplified models based on finite element (FEM) and limit equilibrium (LEM) methods. For all cases, a basin, a rock foundation, an embankment has been defined as the main elements of the tailing dam. The basin is modelled as a shallow layer (slurry tailings) and a deep layer made up of consolidated silty tailings. Deformability, shear strength and hydraulic properties of each material are defined in Table 1. The embankment is 30 meters high with a 2:1 slope and has been assumed to be stage-raised by upstream, downstream and centreline technique (Fig. 3). Soils and rock foundation have been modelled as an elasto-perfectly plastic behaviour with a Mohr-Coulomb failure criterion. LEM analyses have been carried out using of Slide2 v.9.0 code (RocScience), while FEM stability analyses have been performed by RS2 v.08 software (RocScience) with 3111 triangular meshes.

Table 1. Materials parameters: unit weight (γ), cohesion (c'), friction angle (φ), Young's modulus (E), Poisson's ratio (ν), saturated permeability (k_s), ratio between horizontal and horizontal permeability (k_h/k_v).

Material	γ (kN/m^3)	c' (kPa)	φ (°)	E (MPa)	ν (-)	k_s (m/s)	k_h/k_v (-)
Embankment – compacted tailings	21.0	8.0	35	120	0.3	$7{\cdot}10^{-7}$	1.0
Basin – consolidated tailings	16.0	12.0	18	10	0.3	$2{\cdot}10^{-7}$	10.0
Basin – slurry tailings	15.0	0.0	5	2	0.3	$3{\cdot}10^{-5}$	4.0
Foundation	27.0	1000	40	2000	0.3	$1{\cdot}10^{-9}$	1.0

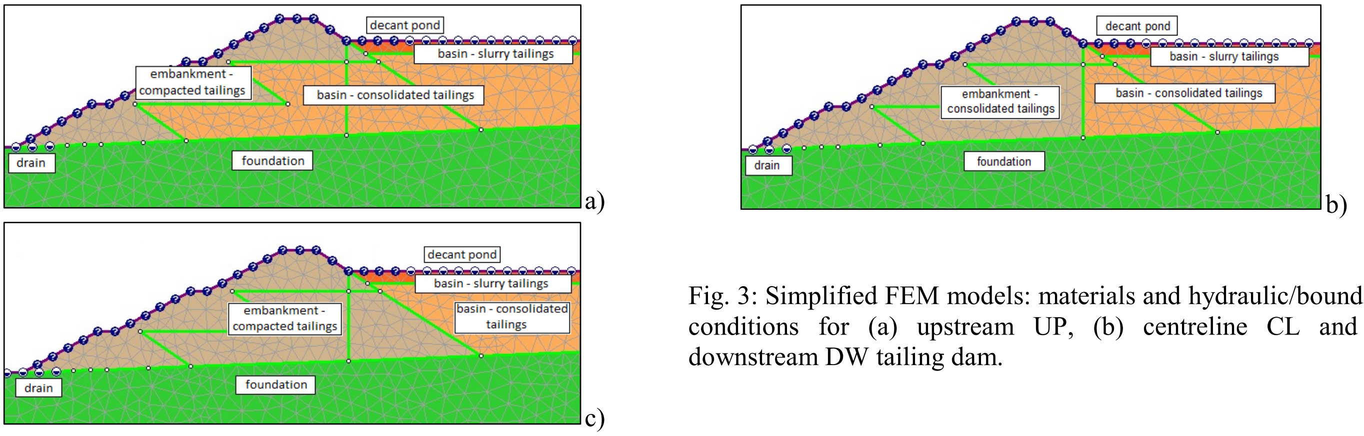


Fig. 3: Simplified FEM models: materials and hydraulic/boundary conditions for (a) upstream UP, (b) centreline CL and c) downstream DW tailing dam.

In the FEM numerical model, the horizontal boundaries are restrained along the X-axis (horizontal) and vertical displacements at the bottom of the model are fixed. Appropriate hydraulic boundary conditions in terms of hydraulic head and pore pressures are applied to the numerical model. For FEM models, the safety factor (S.F.) has been computed by means of an iterative automatic procedure named Shear Reduction Method (SRM). Strength parameters (friction angle in terms of tan φ and cohesion c') are progressively reduced to a certain amount until the failure occurs, implying the system doesn't reach the desired convergence, often termed as Shear Reduction Factor (SRF). The Shear Reduction Factor at failure represents the Critical Strength Reduction Factor (CSRF). The total multiplier ΣM_{sf} was used to define the value of the soil strength parameters at a certain stage in the analysis:

$$\sum Msf = \left(tan\Phi_{input}/tan\Phi_{reduced}\right) = \left(c'_{input}/c'_{reduced}\right) \tag{1}$$

where the strength parameters are labelled as 'input' which refer to the properties entered in the material sets, while parameters labelled as 'reduced' refer to their reduced values used in the analysis. At the beginning of a calculation, the total multiplier ΣM_{sf} is imposed equal to 1 to set all material strength to their unreduced values. Later, strength properties of materials are gradually reduced, so the total multiplier is increased. When the failure occurs, the system is not stable, and the safety factor is defined as:

$$S.F. = available\ strength/strength\ failure = value\ of \sum Msf\ \ at\ failure \tag{2}$$

On the other hand, the use of models based on the Limit Equilibrium Method implies the evaluation of the safety factor of a critical surface defined by means of iterations:

$$S.F. = \frac{\int \tau_r(\sigma_n)dl}{\int \tau_n dl} = \frac{\sum F_{RESISTING}}{\sum F_{MOBILISING}} \tag{3}$$

where the term $\Sigma F_{RESISTING}$ depends on the distribution of normal stresses and strength properties on the sliding surface, while the term $\Sigma F_{MOBILISING}$ is obtained by considering static equations. The safety factor is computed by means the simplified Bishop method of slices:

$$S.F. = \frac{\sum_{i=1}^{n}[c_i'\Delta x_i+(W_i-u_i\Delta x_i)tan\varphi_i][1/m(\alpha_i)]}{\sum_{i=1}^{n}W_i sen\alpha_i+\sum_{i=1}^{n}Q_i e_i/R} \quad ; \quad m(\alpha_i) = cos\alpha_i + \frac{tan\varphi_i \cdot sen\alpha_i}{S.F.} \qquad (4a,b)$$

where Δx_i is the width of the i-th slice, α_i is the angle of the i-th slice bottom with the horizontal slice, W_i is the weight of the slice, c_i' and φ_i are the cohesion and the friction angle that develop along the potential failure surface respectively, u_i is the average pore water pressure at the bottom of the slice, Q_i is the horizontal inertial force, R is the radius of circular failure surface, e_i is the vertical height between Q_i and centre of the failure circle.

3. Numerical results and comments

Section 3.1 is aimed at showing the influence of numerical approach – FEM or LEM respectively and the position of the piezometric line on the stability of the tailing dam. Then, the influence of geometry of drainage system and distance of decant pond on the stability of the embankment is investigated in section 3.2. Finally, section 3.3 provides some considerations concerning the effects of the uncertainly on geotechnical properties of tailings on the stability of the embankment.

3.1. Influence of numerical approach and water table on the stability of the embankment

Analyses were aimed at evaluating the influence of different numerical approaches on the safety factor in dry conditions. Finite element method (RS2) and limit equilibrium method (Slide2) are the two numerical modelling approaches adopted in the current study: in the latter case, the safety factor has been evaluated using the simplified Bishop approach. Stability analyses were performed by considering the three raising techniques and no water table (Fig. 4a, Table 2). While downstream and centreline methods seem to be giving similar values of safety factors, whereas, upstream raising technique results in a lower safety factor. These considerations arise from both numerical approaches as shown in Fig 4a, where solid black line represents results obtained by FEM and dotted black line represents those obtained by LEM. It's worth noting a difference of about 7%-12% in terms of absolute values between outcomes resulting from the two different approaches. Despite some differences due to geometry of the embankment and geotechnical properties of materials, similar results were obtained by [13] by comparing the influence of the raising method and numerical approach on the stability of upstream and downstream raised dams in dry conditions (Table 3). The Authors obtained differences of 2%-5% between FEM and LEM method. As shown in the current study, the Authors obtained higher safety factors if the finite element method is adopted, and this consideration can be extended both for finite element method and limit equilibrium analyses.

Table 2. Safety factors obtained in the current study by considering different raising methods/numerical approaches (dry conditions).

Safety factor, S.F.	Upstream method (UP)	Downstream method (DW)	Centreline method (CL)	Difference		
				UP-DW	UP-CL	DW-CL
RS2 (FEM)	1.53	2.09	2.05	27%	2%	25%
Slide2 (LEM)	1.64	1.82	1.82	10%	0%	10%
Difference FEM-LEM	7.0%	12.0%	11.0%		-	

Table 3. Safey factors obtained by [13] for different raising methods and numerical approaches (dry conditions).

Safety factor, S.F.	Upstream method (UP)	Downstream method (DW)	Difference UP-DW
RS2 (FEM)	1.42	1.53	8.0%
Slide2 (LEM)	1.39	1.46	5.0%
Difference FEM-LEM	5.0%	2.0%	-

Further analyses have been carried out to evaluate the influence of the water table on the stability of the embankment, depending on the raising method. Three simplified FEM models, one for each raising technique, were generated by placing the water table behind the embankment to simulate the presence of the decant pond. Results were then compared with those obtained from three similar FEM models with no water table (Fig. 4b). It is possible to observe that the water table plays a crucial role in terms of stability of the embankment by decreasing the safety factor of about 30% in all the cases. It can be observed that the raising technique has a fundamental role, so the upstream method seems to be the most unsafe technique both for tailings in dry or saturated conditions, while downstream and centreline techniques provide similar results in terms of safety factor. Again, considering some differences due to geometry and geotechnical properties of materials, [13] obtained results that, in general terms, can be compared with those of the current study. In saturated conditions, the Authors observed that the upstream method gives lower safety level than downstream method, both by using FEM or using LEM approaches.

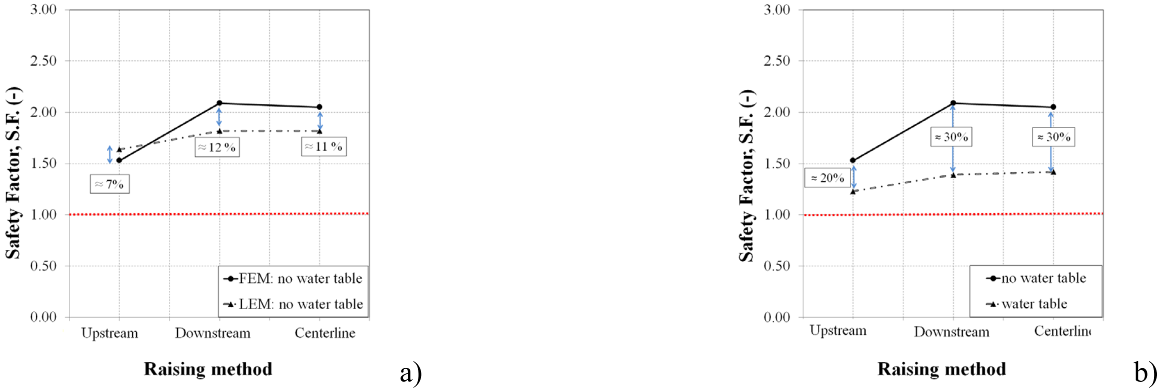
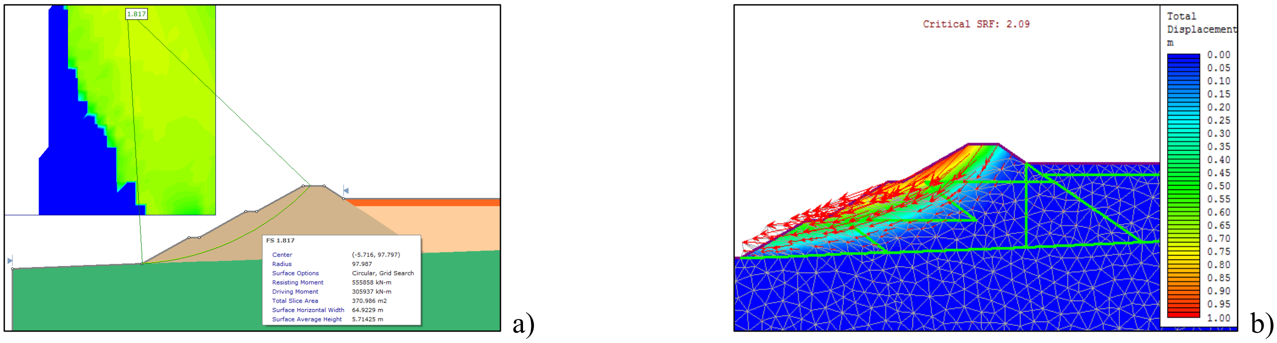


Fig. 4: a) Influence of numerical method on the safety factor, b) Influence of water table on the safety factor both for finite element method and limit equilibrium method.



FS 1.817
Center (-5.716, 97.797)
Radius 97.987
Surface Options Circular, Grid Search
Resisting Moment 555858 kN-m
Driving Moment 305937 kN-m
Total Slice Area 370.986 m2
Surface Horizontal Width 64.9229 m
Surface Average Height 5.71425 m

Fig. 5: Stability analysis of the embankment for downstream method in dry conditions with a) Limit Equilibrium Method ($S.F_{min}$=1.82), and b) Finite equilibrium method (S.F.=2.09).

These results suggest that a critical comparison with different numerical approaches could be useful to assess reliable stability analysis. Despite its simplicity, LEM could give a first estimation of the safety factor (Fig. 5a), while more sophisticated FEM analysis can be used to assess the stress-strain behaviour of the embankment (Fig. 5b).

3.2. Influence of geometry of drainages and distance of decant pond on the stability of the embankment

According to [14], the phreatic surface plays a fundamental role in the stability of tailing dams, under both static and seismic conditions, hence one of the most important rules in the design phase is that the phreatic surface should be kept as low as possible and it should not emerge from the dam face. Aimed at decreasing the water pressure and lower the water surface, drainage systems are often adopted in waste storage facilities. In order to evaluate the influence of different drainage systems, stability analysis of the embankment by including simplified drainage systems with different length are performed. The presence of drains was simulated by including element at zero pore pressure placed at the toe of the embankment for the three raising techniques. Results suggest that the length of the horizontal drain has a significant role both for upstream and centreline or downstream raising techniques (Fig. 6a, Fig. 7). Higher length of the drain results in greater safety factor. An increase of about 30%-40% could be observed for all raising methods if the S.F. are compared in the case of no drains or 40 m long drains. No variations in the safety factor seem to occur when the drainage system exceeds certain lengths (40 m in the current study) and no relevant differences of the safety factor can be appreciated between upstream and centreline raising method. It can be noted that in the current research, according to [13], a highly efficient drainage system seems to be able to guarantee an adequate safety level also for upstream tailing dams. This can be observed by the rapid increase of the safety factor with drainage length as highlighted in Fig. 6a (dashed line). Another factor affecting the position of the phreatic surface and, in turn the overall stability of tailing dams, is the location of the ponded water with respect to the dam embankment ([14]). In the current research, the influence of the distance of the decant pond from the top of the embankment has been evaluated and results are summarized in Fig. 6b. Generally, higher is the distance of the pond from the dam, greater is the safety factor. Again, downstream and centreline techniques give similar results in terms of safety factor.

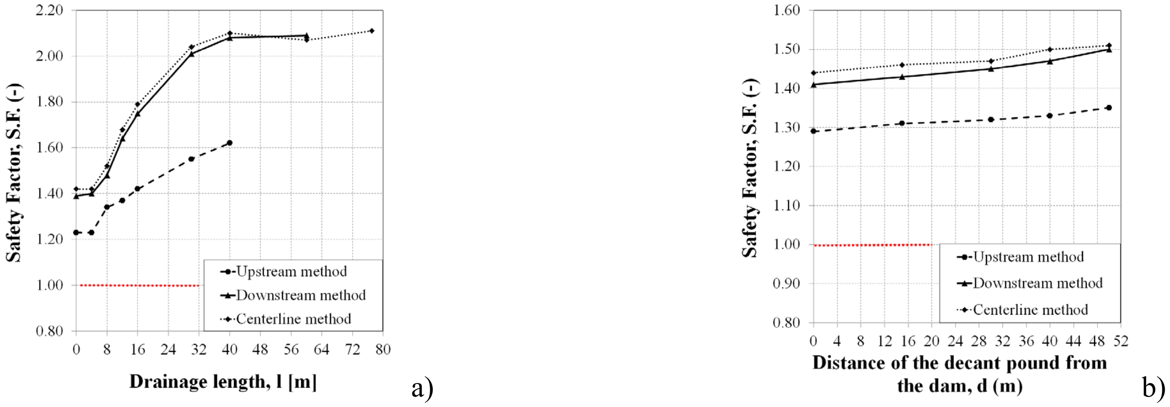


Fig. 6: a) Evolution of the safety factor with the length of drains installed at the toe of the embankment for the three raising methods; b) Influence of the distance of the decant pond on the stability of the embankment.

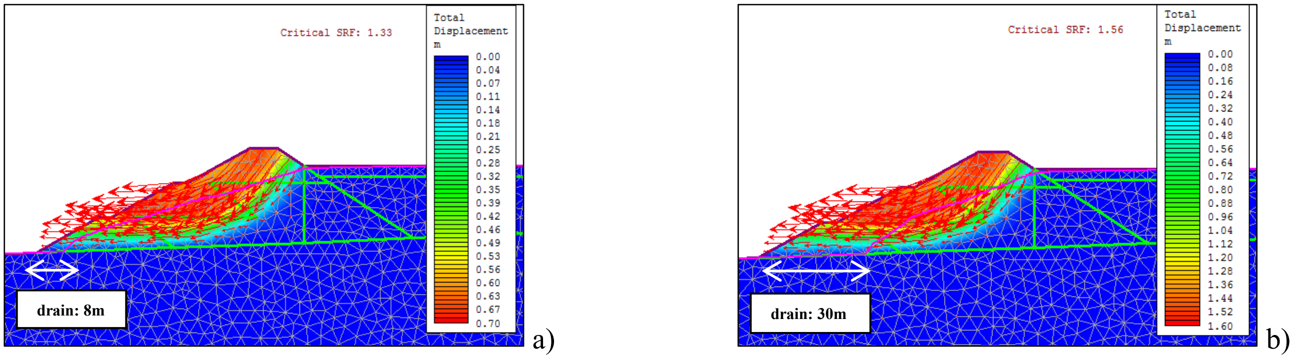
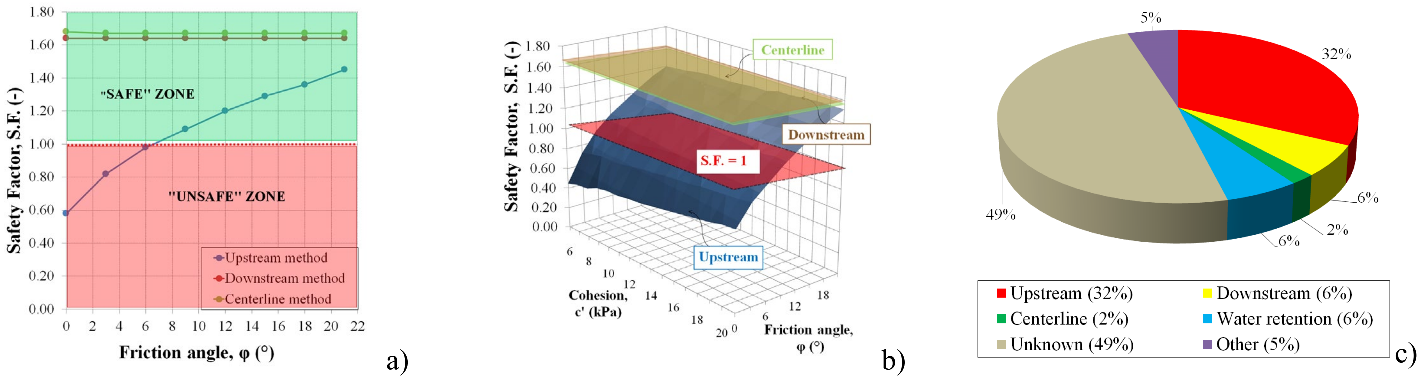


Fig. 7: a) FEM Stability analysis of the embankment for the upstream method with a) drains 8 meters long (S.F.=1.33), and b) drains 30 meters long (S.F.=1.56).

3.3. Influence of the mechanical properties of tailings on the stability of the embankment

In order to evaluate the influence of the shear strength of deeper layer of deposited tailings on the stability of the embankment, friction angle and cohesion of consolidated tailings have been gradually decreased. Simplified FEM models of the three rising methods have been implemented by ranging friction angle from 0° until 21° and cohesion values from 6 kPa until 21 kPa. Results obtained by considering a constant value of cohesion equal to 12 kPa and just changing the friction angle are shown in Fig. 8a. It is evident that the upstream method rising technique most affected by the variations of geotechnical properties of tailings. Relevant variations of the safety factor can be observed, from S.F. ($\varphi = 0°$) = 0.60 until S.F. ($\varphi = 21°$) = 1.40, which implies that for some geotechnical scenario the stability of the embankment could not be guaranteed. Figure 8a is a cross section of a three-dimensional representation obtained by varying simultaneously cohesion and friction angle (Fig. 8b). Both those variations seem to considerably affect the stability of the embankment, especially for the upstream rising technique (blue surface), while downstream and centreline rising methods (sub-horizontal brown and green planes) seem not to be affected greatly by variation of the geotechnical properties of deposited tailings. According to [15], these results suggest that, if the upstream technique is adopted as the raising method because of its low costs or some logistic advantages, the stability of the embankment widely depends on the shear properties of deposited tailings, leading to a higher number of collapsed if compared with other raising methods (Fig. 8c).



a) b) c)

Fig. 8: a) Evolution of the safety factor with the friction angle at a constant value of cohesion equal to 12 kPa; b) 3D representation of the safety factor; c) number of worldwide failures, depending to the raising method and type of dam, up to 2022 (modified from [16]).

4. Conclusion

Because of their relevant spatial extension, long operation-life, raising methods, deposition techniques and high rate of failures associated at serious social and environmental impacts, tailing dams represent complex geotechnical systems needing detailed investigations during monitoring and design phases. The stability of a hypothetic embankment has been studied by considering relevant factors that affect its safety level. Some simplified stability analyses have been carried out by considering the influence of numerical approach, geometry of drainage systems, raising method, distance of the decant pond from the embankment and geotechnical properties of deposited tailings on the safety factor. Numerical results conclusively showed that some of these factors represent key elements in terms of stability of the embankment. According to the many Authors, despite its time and economic benefits, the upstream method seems to be the most unsafe raising technique. According to literature results, it was proved that if the embankment is upstream grow type, stability analysis shows that the safety will be guaranteed just by shear properties of deposited tailings, but due to the great variability of tailing properties this could be a critical factor. Furthermore, it was observed that, even for upstream embankment, the safety level increases rapidly with appropriate drainage systems. It is worth to note that further analysis could be performed by considering coupling between all these factors, including other different drainage geometries, the presence of inner cores or permeability variations to cover a wider range of cases. Additional and more detailed numerical evaluations should be done by modelling tailing wastes as materials with the capacity to generate pore pressure that was proved to be responsible of many failures due to liquefaction trigger mechanism. Finally, other analysis could also consider the aging effects related to particle rearrangement resulting in macro-interlocking of particles and micro-interlocking of surface roughness.

References

[1] G. Bella, ”Water retention behaviour of tailings in unsaturated conditions”, *Geomechanics and Engineering, An Int'l Journal*, vol. 26, no. 02, pp. 117-132, 2021.

[2] G. Bella, “Hydro-Mechanical Behaviour of tailings in Unsaturated Conditions” *Ph.D. dissertation*, Dept. Struct. Build. and Geotech. Eng., Politecnico di Torino, Italy, 2017.

[3] G. Bella, “Mechanical response of tailings under monotonic triaxial tests in unsaturated and nearly saturated conditions”, *Proceedings of the 8th Int. Conf. on Geotechnical Research and Engineering (ICGRE 2023)*, Lisbona – March, 29/31, 2023.

[4] G. Bella and G. Musso, “Experimental study of the hydro-mechanical behaviour and Critical State Conditions of unsaturated silty tailings”, *Proceedings of the 8th Int. Conf. on Geotechnical Research and Engineering (ICGRE 2023)*, Lisbona – March, 29/31, 2023.

[5] G. Bella, M. Barbero, F. Lameiras, T. Esposito and F. Barpi, “Chemical-Physical Characterization of Stava Tailings Subjected to an Innovative Aging Technique”, *Proceedings of the 7th Int. Conf. on Geotechnical Research and Engineering (ICGRE 2022)*, Online – April, 10-12, 2022.

[6] G. Bella, F.S. Lameiras, T. Esposito, M. Barbero and F. Barpi, ”Aging Simulation of the Tailings from Stava Fluorite Extraction by Exposure to Gamma Rays”, *Revista Escola de Minas*, vol. 70, no. 04, pp. 483-490, 2017.

[7] F. Lameiras, C. Freire and G. Bella, “A preliminary insight of the effects of tailing wastes addition on metakaolin-based geopolymers”, *Proceedings of the 8th Int. Conf. on Geotechnical Research and Engineering (ICGRE 2023)*, Lisbona – March, 29/31, 2023.

[8] Australian Committee on Large Dams (ANCOLD 2011). Guidelines on tailings dams - planning, design, construction, operation and closure, Australia.

[9] M. Davies, T. Martin and P. Lighthall, “Mine Tailing Dams: When Things Go Wrong”, *Tailing Dams 2000. Association of State Dam Safety Officials, U.S. Committee on Large Dams*, Las Vegas, pp. 261-273, 2000.

[10] M. Rico, G. Benito, A. Salgueiro, A. Dıez-Herrero and H. Pereira, “Reported tailings dam failures - A review of the European incidents in the worldwide context”, *Journal of Hazardous Materials*, vol. 152, no. 02, pp.846-852, 2008.

[11] Z. Lyu, J. Chai, Z. Xu, Y. Qin and J. Cao, “A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History”, *Advances in Civil Engineering*, pp. 1-18, 2019.

[12] F. Carmo et. al., “Fundão tailings dam failures: the environment tragedy of the largest technological disaster of Brazilian mining in global context”, *Perspectives in Ecology and Conservation*, vol. 15, no. 03, pp. 145-151, 2017.

[13] F. Cardozo and A. Zingano, “Consideracoes e comparacoes entre metodos construtivos de barragens de rejeito”, *Proceedings of the 9º Congresso Brasileiro de Minas a Céu Aberto e Minas Subterrâneas*, Belo Horizonte/MG, 2018.

[14] USCOLD, TDI, US Committee on Large Dams, USCOLD, Denver, CO, 1994.S. Vick, “Planning, Design and Analysis of Tailing Dams”, BiTech Publishers Ltd, 1990.

[15] P. Croce, “Criteri di progettazione dei bacini di decantazione”, *Proceedings of the Conference: Progetto, gestione e controllo dei riempimenti di terra, bacini di decantazione e colmate, discariche*, Stava – July, 16/17, 2015.

[16] L. Piciullo, E.B. Storrøsten, Z. Liu, F. Nadim and S. Lacasse, “A new look at the statistics of tailings dam failures”, *Engineering Geology*, vol. 303, pp. 1-14, 2022.