Performance assessment of a filtered tailings storage facility partially built with uncompacted tailings

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Abstract

Common practice of dry stacking or filtered tailings disposal includes stacking, spreading, aeration to reduce moisture provided by the filtration plant, and compaction with smooth vibratory rollers, all of which to expect a material with dilative behaviour, adequate strength and very low liquefaction potential, contributing to the stability of the facility without the need for large retention dams. These processes involve significant operating costs for the disposal of filtered tailings, which is one of the main restrictions for the use of this technology. This work has focused on analyzing the static behavior of a filtered tailings storage facility, which will be built by dividing the facility into two zones. 1) structural zone made up of compacted tailings to ensure the overall stability of the facility; and 2) non-structural zone made up of filtered tailings disposed as received, that is, without compaction. The inherent risk of this solution is that the relatively low initial degree of saturation of the uncompacted tailings in loose conditions, may be increased by the static loads of the tailings disposal up to the saturation, making it susceptible to static or seismic liquefaction. The geotechnical parameters of the foundation soils and the filtered tailings were estimated based on field and laboratory geotechnical investigations. The tailings disposal operation was simulated through numerical modelling using Sigma/W, in which the uncompacted filtered tailings were analyzed by the NorSand model. The simulation results indicated that it is possible to place uncompacted filtered tailings, thereby reducing operating costs, but this requires reducing the moisture content of these materials to at least the optimum to prevent liquefaction and ensure the overall stability of the facility.

Introduction

Nowadays, there is not much research conducted on filtered tailings. Additionally, in recent years, the number of tailings dams built using this technology has been increasing due to its safety advantages compared to more traditional tailings disposal procedures (Copeland et al., 2023; Cacciuttolo and Perez, 2022; Pizarro and Olivares, 2018; Davies and Rice, 2001; Hambley and Verbeek,2020).

Filtered tailings are usually placed in the storage facility and spread to promote moisture loss until reaching the optimum moisture content, after which they are compacted to increase their strength and generate a self-supporting structure. This process requires a high operating cost, which is one of the main restrictions for the use of this technology. Therefore, with the aim of reducing costs, the following questions arise: is it necessary to reduce the moisture of the filtered tailings below the values obtained in the filtration plant? Is it possible to place the filtered tailings, or at least part of them, uncompacted without compromising the structural integrity of the facility? This research aims to answer these questions.

Filtered tailings basic characteristics

The filtered tailings are classified as non-plastic sandy silt, ML, the fines content varies from 63 to 71%, the liquid limit is between 17 and 19 and the plasticity is very low to non-plastic. The uncompacted filtered tailings have a hydraulic conductivity of 1.3×10^{-6} to 7.3×10^{-7} cm/s.

Initial configuration of the FTSF

Structural and non-structural zones

To guarantee the proper stability condition of the projected filtered tailings storage facility (FTSF), a shell or structural zone needs to be build consisting of structural fill, that is, filtered tailings compacted to the 95% of its its maximum dry density according to the standard Proctor in layers of up to 50 cm. Behind this shell, uncompacted tailings will be placed by dumping with trucks.. With the objective of an initial determination of the structural zone extension, a limit equilibrium analysis was performed.

Stability analysis of the initial configuration

Stability assessments were carried out through limit equilibrium analyses of the section shown in Figure 1, using the Slope/W module from Geostudio software (2023 using the Spencer's procedure (1967) alongside the cuckoo search algorithm by Yang and Deb (2010). These analyses were carried out by modifying the extension of the structural zone (Tailings C) and considering the most critical behavior of the uncompacted tailings (Tailings NC), that is, an undrained response, static or seismic liquefaction of these materials and their characterization through their residual strength. Pore water pressure has not been considered in this preliminary analysis. Based on triaxial testing results, Tailings C material was modeled with a density of 20 kN/m^3, zero cohesion and angle of friction of 35 degrees, while Tailings NC was modeled with density of 14 kN/m^3 and undrained residual strength ratio of S_{ur}/σ'_0=0.11 obtained conservatively from a monotonic simple shear test after liquefaction by cyclic loading. The required post-liquefaction factor of safety (FoS) for this analysis mut be equal to or greater than 1.2, which is considered acceptable for a post-liquefaction condition according to the Canadian Dam Association (CDA, 2019).

Figure 1 shows the most critical failure surface based on the limit equilibrium analysis, it was concluded that the extension of the structural zone (Tailings C) must be at least 250 meters to guarantee the stability of the FTSF for a critical condition represented by the liquefaction of the uncompacted tailings.

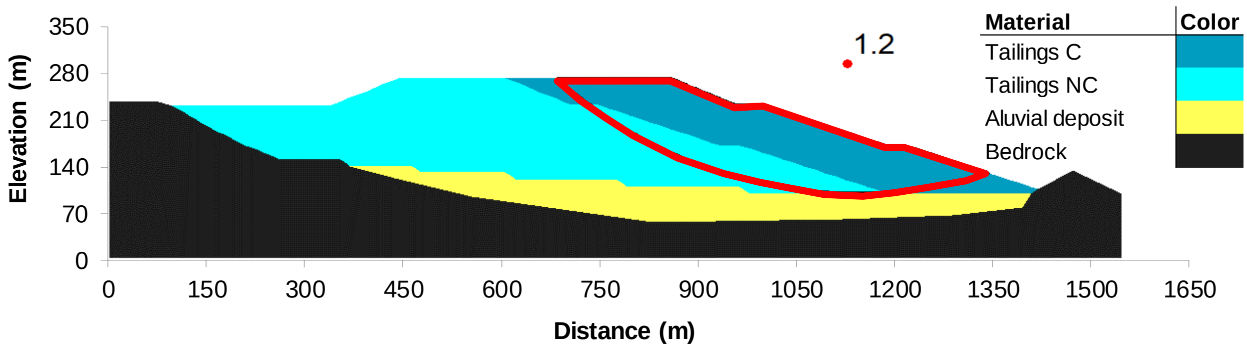

Figure 1: Section analyzed for definition of the structural zone

Cases analyzed

Two cases were analyzed, in both of them the moisture content of Tailings C material was reduced from 20% (as received from the filtration plant) to the optimum which is 16% achieved after *in situ* drying by aerating, and compacted at 95% of their maximum dry density of 17.3 kN/m³ based on standard Proctor, to try to produce a material with essentially dilative behavior. Uncompacted filtered Tailings NC were disposed by stacking, exhibiting contractive behavior.. Foundation consists of a sand alluvial deposit classified as SM overlying an andesite bedrock (see Figure 1).

Oedometer test results

Figure 2 shows the results of oedometer test conducted on Tailings NC, where a variability in void ratios and degree of saturation was observed, primarily influenced by their density and initial moisture content. Based on the oedometer testing, the maximum and minimum envelopes were evaluated to establish the initial void ratio for each lift of the Tailings NC, assuming an average lift of 5 meters thick that provides a vertical stress of 70 kPa and considering that the control nodes are located in the middle of each lift.

According to Aghazamani *et al.* (2021), soils with equal to or greater than 80% saturation and with a contractive behavior, are prone to liquefaction, thus, an undrained behavior was chosen for such conditions.

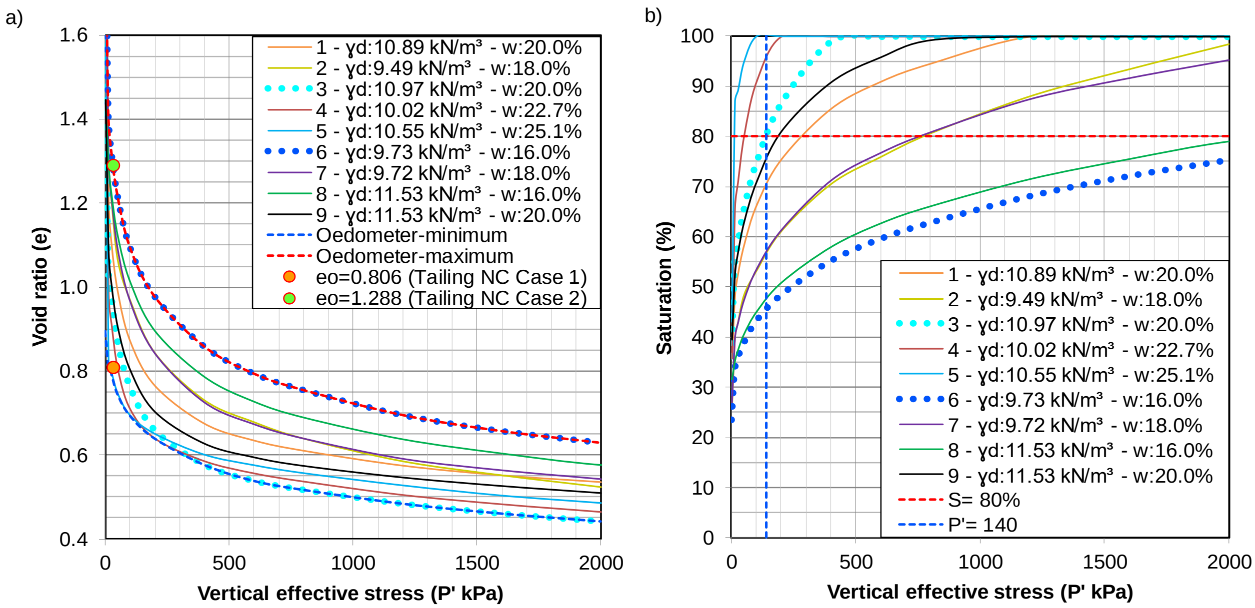

Figure 2: Oedometer curves of a) vertical stress vs. void ratio and b) vertical stress vs. saturation

Case 1

It represents the conditions of the uncompacted filtered tailings with the average moisture content obtained from the filtration plant which is 20%. The initial void ratio was assumed to represent the lower envelope of the oedometer curves (see Figure 2a), corresponding to tailings filtered at a vertical stress of 35 kPa (half a lift), resulting in an initial void ratio of 0.806 and a corresponding degree of saturation of 60% (Figure 2b) which is a relatively high initial value. According to Figure 2b, 80% saturation (threshold value below which conditions are essentially drained,) is reached with a vertical stress of 140 kPa, which corresponds to loads transmitted by two lifts (Tailings NC-D1 in Figure 3); layers from the bottom to the top generate greater stresses and therefore, saturation degrees greater than 80%, so Tailings NC-U in Figure 3 were analyzed in undrained condition.

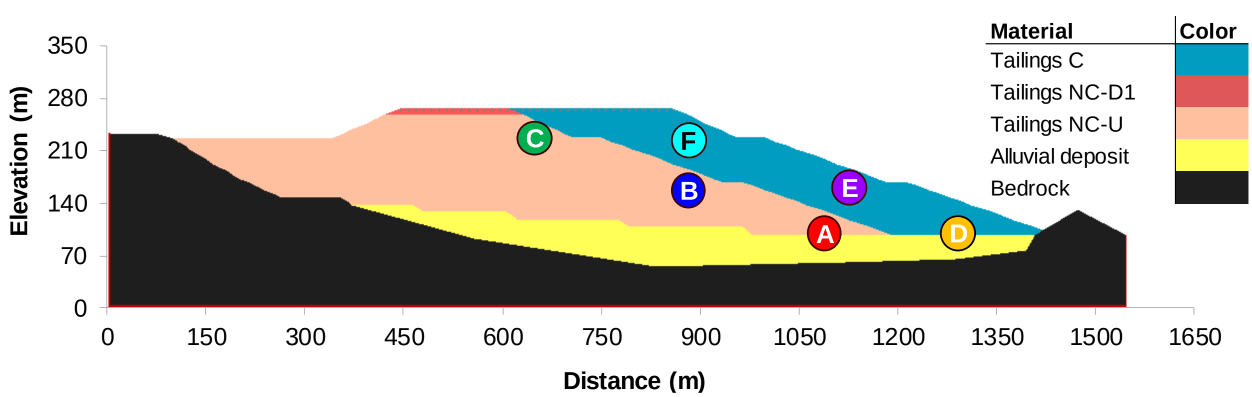

Figure 3: Section analyzed for Case 1

Case 2

Represents the conditions of uncompacted filtered tailings with the optimum moisture content of 16% which is achieved in the same way as Tailings C, i.e. spread in small layers and *in situ* drying by aerating, which increases the operating cost of the FTSF. Based on the oedometer test curves, the upper boundary representing the behavior of uncompacted filtered tailings with 16% moisture content and a vertical stress of 35 kPa, corresponds to an initial void ratio of 1.288 (Figure 2a), the corresponding degree of saturation is 37% (Figure 2b). As can be seen in Figure 2b, the degree of saturation of the selected curve is less than 80% up to 2000 kPa of vertical stress, i.e., higher than the maximum height of the FTSF, therefore, Tailings NC-D2 in Figure 4 were analyzed considering drained behavior.

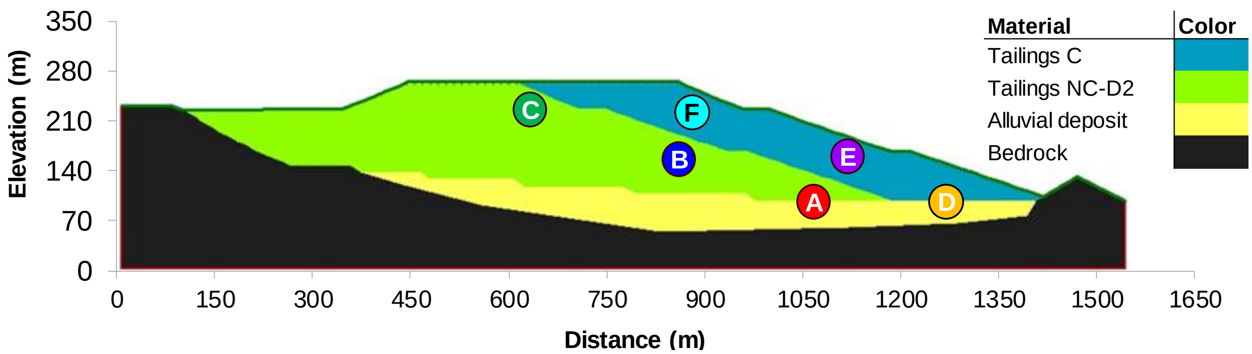

Figure 4: Section analyzed for Case 2

It is important to note that the initial condition (void ratio) for the Tailings C in Case 1 and Case 2, was obtained at the maximum dry density of the standard Proctor, with a dry density of 17.3 kN/m³, a moisture content of 16%. Six representative control points from the initial, intermediate, and final stages of the Tailings NC (A, B and C) and Tailings C (D, E and F) shown in Figures 3 and 4, were considered to compare the contractive and dilative behavior of the filtered tailings.

Performance assessment of FTSF

Constitutive models

In geotechnical numerical modeling, selecting the right constitutive models is crucial for accurate simulations. The NorSand (NS) model, introduced by Jefferies and Been in 2015, is based on critical state soil mechanics, and is adept at simulating static liquefaction and dilatancy in granular materials; its parameters allow for modeling of complex behavior in tailings, demonstrating its effectiveness in predicting the responses of different tailing types under stress and was used for modeling the uncompacted filtered tailings. The Hardening Soil (HS) model, developed by Schanz et al. in 1999, is advanced and non-linear, designed for detailed soil behavior simulation, it incorporates stress limit states with confinementdependent strength and stiffness parameters, essential for realistic soil behavior modeling under high loads, such as in tailings storage facility; this model was used for the compacted filtered tailings and the alluvial foundation soil. The generalized Hoek-Brown (GHB) model, an evolution of the original Hoek-Brown failure criterion, is widely used for modeling rock masses in geotechnical engineering (Hoek et al., 2002) and was used for bedrock modeling. These models, each with distinct advantages, are integral to geotechnical engineering, especially in numerical modeling, for a comprehensive analysis of soil and rock behavior under various conditions.

Numerical modeling

To assess the serviceability of the structure based on deformation, a finite element numerical modeling conducted for Case 1 and Case 2. A plastic analysis was performed, considering lifts of 5 meters, using the Sigma/W module of the Geostudio software (2022). These analyses were performed to identify liquefaction zones of the Tailings NC (Case 1), magnitude of displacements in the whole structure, stress path in the control points within the FTSF, among other factors. In Case 1, the criteria for conducting this analysis was based on the drained behavior of the Tailings NC for the first 10 meters raise (2 lifts), followed by an undrained behavior of this material for deeper layers. In contrast, for Case 2, all layers were modeled with drained behavior, as determined from oedometer tests.

Geotechnical characterization

For this study, a field investigation and laboratory testing program were conducted for the characterization of the foundation soil, including drillholes, test pits and geophysical surveying. The geotechnical characterization of the filtered tailings was performed based on laboratory testing including oedometer and drained and undrained isotropically consolidated triaxial tests to characterize material strength. Also, information from literature (Robertson et al., 2017), and Anddes' project database were used to characterize the geotechnical properties of the foundation and tailings. For finite element method (FEM), Norsand constitutive model was calibrated according to Jefferies and Been (2015), while Hardening Soil and Generalized Hoek-Brown models were calibrated based on Geostudio (2022) (see Tables 1 and 2). Figure 5 shows the calibration for the uncompacted tailings with the triaxial tests performed.

Table 1. Summary parameters for the FEM, tailings (NS)

	Tailing NC-U (Case 1)	Tailing NC-D1 (Case 1)	Tailing NC-D2 (Case 2)	Tailing C (Case 1 and 2)
Color				
Response	Undrained	Drained	Drained	Drained
e_0	0.806	0.806	1.288	0.59
H_0	72.3	72.3	72.3	100
H_y	72.1	72.1	72.1	0
γ (kN/m^3)	14	14	14	20
G_0 (MPa)	30	30	30	151
m	0.2	0.2	0.2	0.05
OCR	1.3	1.3	1.3	1.3
ν	0.2	0.2	0.2	0.2
Pref	100	100	100	100
M_{tc}	1.6	1.6	1.6	1.6
N	0.1	0.1	0.1	0.3
X_c	2.9	2.9	2.9	4.0
C_a	2.35	2.35	2.35	2.35
C_b	1.72	1.72	1.72	1.72
C_c	0.03	0.03	0.03	0.03
Γ	0.88	0.88	0.88	0.88
λ	0.0538	0.0538	0.0538	0.0538
S	0.5	0.5	0.5	0.5

Table 2. Summary parameters for the FEM, foundation

	Alluvial deposit (HS)	Bedrock (GHB)
Color		
Response	Drained	Drained
ϕ (°)	35	(-)
ν	0.2	0.2
γ (kN/m^3)	20	26
E (kN/m^2)	(-)	60E6
E_{50} (kN/m^2)	10.5E3	(-)
E_{oed} (kN/m^2)	10.5E3	(-)
E_{ur} (kN/m^2)	31.5E3	(-)
m	0.87	(-)
Rf	0.94	(-)
UCS (kPa)	(-)	190
mb	(-)	0.36
s	(-)	0
a	(-)	0.51

Finite element analysis

Figure 6 shows the finite element mesh of the numerical analysis of Case 1 with the discretization for each material; similar mesh was prepared for the Case 2 analyzed. For both cases, the FTSF raise was simulated by 34 lifts of 5 meters thickness. For Case 1 where the conditions are undrained, the dissipation of pore water pressure generated during disposal has not been considered, due to the very low permeability of the filtered tailings, even when not compacted, which significantly reduces the water flow.

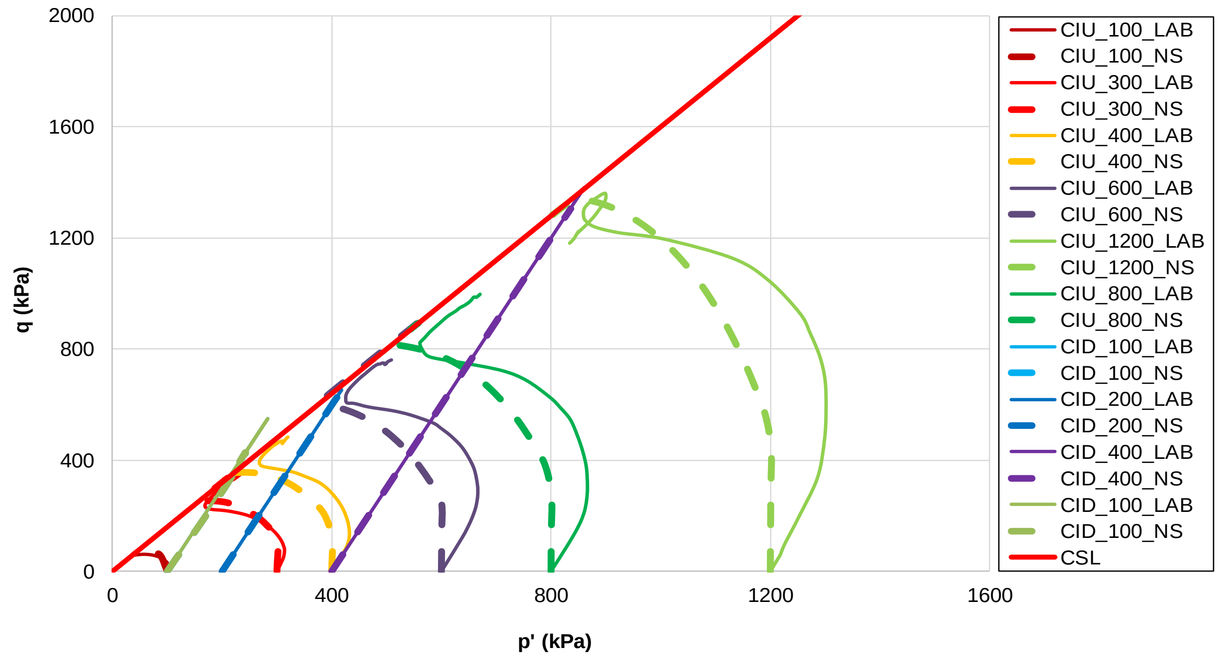

Figure 5: Model calibration based on triaxial tests. p′ -q diagram

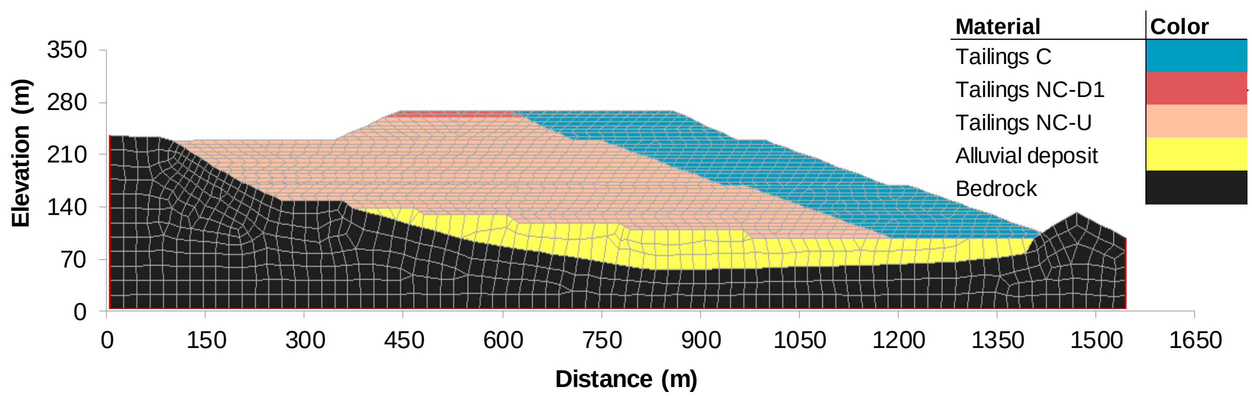

Figure 6: Finite element mesh for analysis of Case 1

Figures 7a and 7b show the p' vs q and p' vs void ratio (e) graphs during the filtered tailings disposal. In Figure 7a, for Case 1 and Case 2, where M is the critical state stress ratio defined based on drained and undrained triaxial tests performed to determine the critical state line (CSL), and IL is the instability line defined as the maximum q value after which the critical state is reached. As can be seen in Figure 7a, the stress paths of control points A, B and C (Tailings NC-U) for Case 1 show a clear contractive trend, reaching the instability line at $\eta = q/p' = 0.74$, and then liquefaction at the critical state, while points D, E and F (Tailings C) show a dilative behavior. For Case 2, the stress paths in all cases do not show a contractive trend or decrease in effective stress, that is because the saturation degree is less than 80% with no generation of excess pore pressures. Figure 7b shows that points A, B and C for Case 1, reach the CSL and static liquefaction occurs, while points D, E and F are far from the CSL. The same analysis was performed for the entire finite element model.

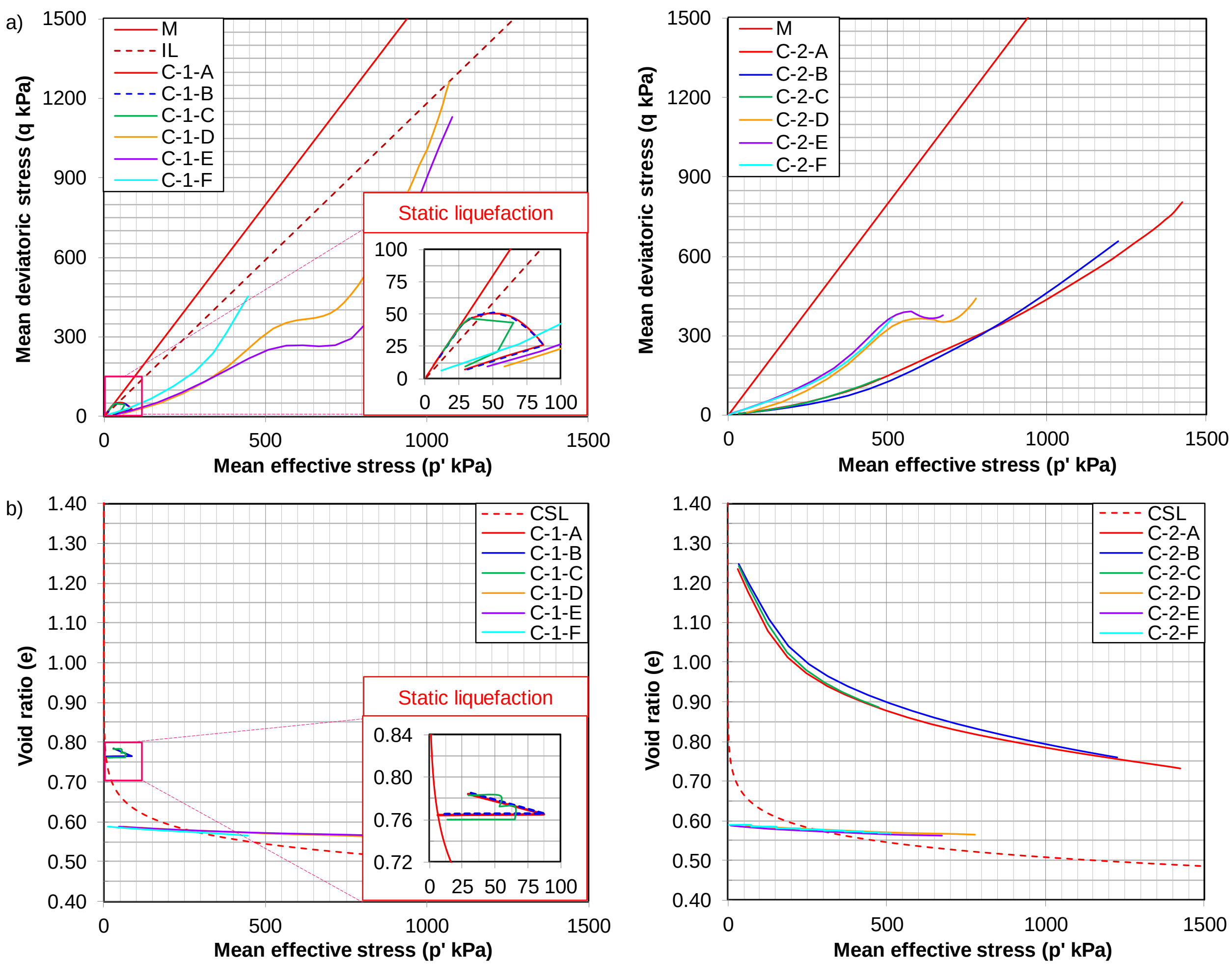

Figure 7: a) p'-q and b) p vs e, during filtered tailings disposal for Case 1 and Case 2

Other criteria for identifying zones of static liquefaction were based on the failure criteria proposed by Geostudio (2022), as presented in equations 1 and 2.

$$|\psi| < 0.001 \quad (1)$$

$$|\eta - M_i| < 0.1 \quad (2)$$

Where ψ is the state parameter.

Figures 8a and 8b show the evolution of the above failure criteria per lift during the FTSF raise. Figure 8a shows that points A and B (Tailings NC-U) reach a $|\psi| < 0.001$ condition for lifts 22 and 32, respectively, predictably achieving the critical state (liquefaction) and fluctuating within a range from 0 to -0.05, while point C does not reach this condition; however, points A, B and C adhere the second criteria ($|\eta\text{-}M_i| < 0.1$) for lifts 16, 22 and 29, respectively, indicating liquefaction at that specific raise.

Figure 8c shows the FTSF raise versus η/M, displaying a rapidly escalating mobilized strength in the Tailings NC-U, particularly after reaching the instability line (η/M=0.74), approaching 1.0 (critical state) indicating liquefaction. Figure 8d shows the rapid increase of the pore water pressure during the FTSF raise.

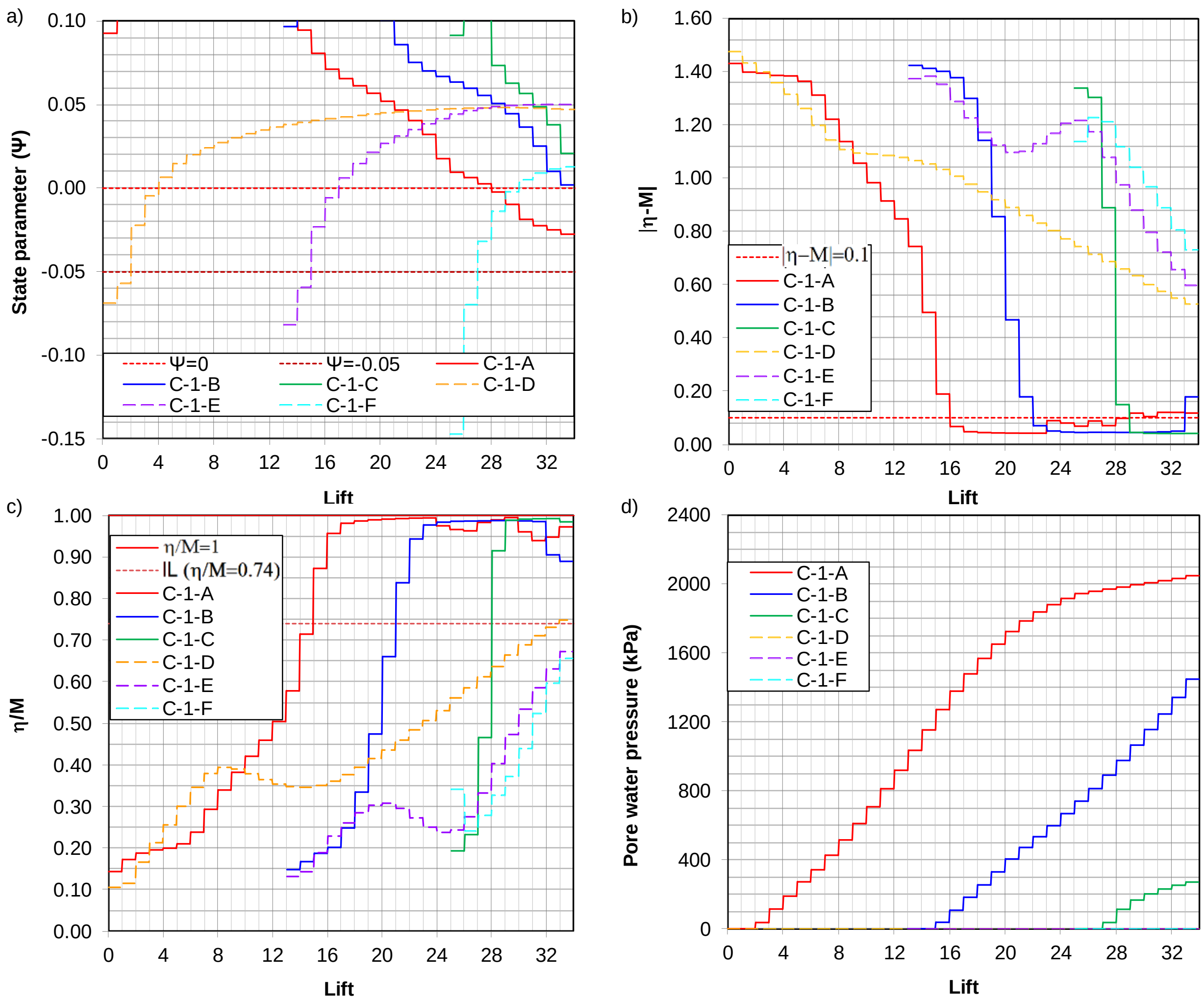

Figure 8: Variation of a) Ψ, b) |η-M|, d) η/M and c) pore pressure, during Case 1 FTSF raise

Figure 9 shows that the NC-U tailings have reached a mobilized strength, η-M, greater than 0.74, surpassing the instability line, indicative of static liquefaction and approaching the critical state.

Horizontal and vertical displacements were calculated at each raise. Figures 10 and 11 illustrate the displacements at the maximum height of the FTSF for Case 1 and Case 2, respectively. For Case 1, maximum horizontal and vertical displacements of 10.3 and 4.3 m, respectively, were obtained, which occurred in the middle and upper part, respectively, of the FTSF at Tailings C. For Case 2, maximum horizontal and vertical displacements of 2.0 and 8.8 m, respectively, were calculated. As expected, horizontal displacements in Case 1 are larger than in Case 2, due to undrained condition which generates predominantly shear strains and liquefaction of uncompacted tailings, while the drained conditions of the uncompacted tailings in Case 2 predominantly generate volumetric strains and vertical displacements (settlements).

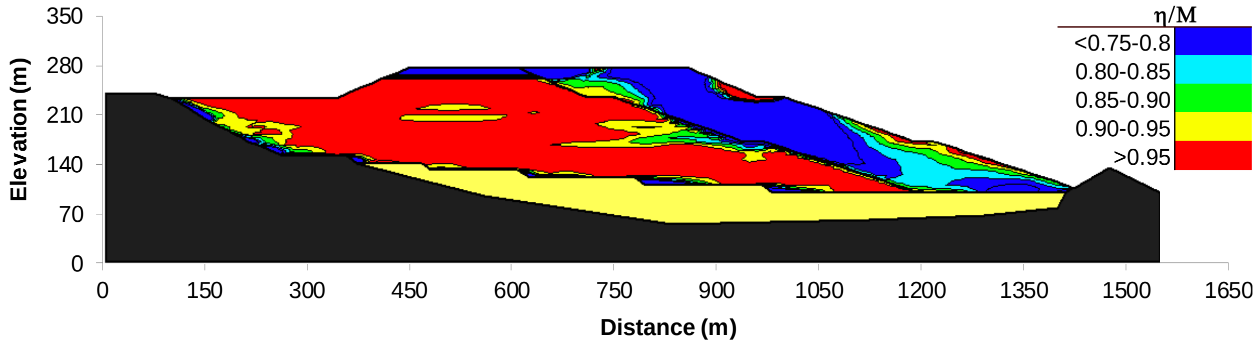

Figure 9: Mobilized strength, η/M. Case 1

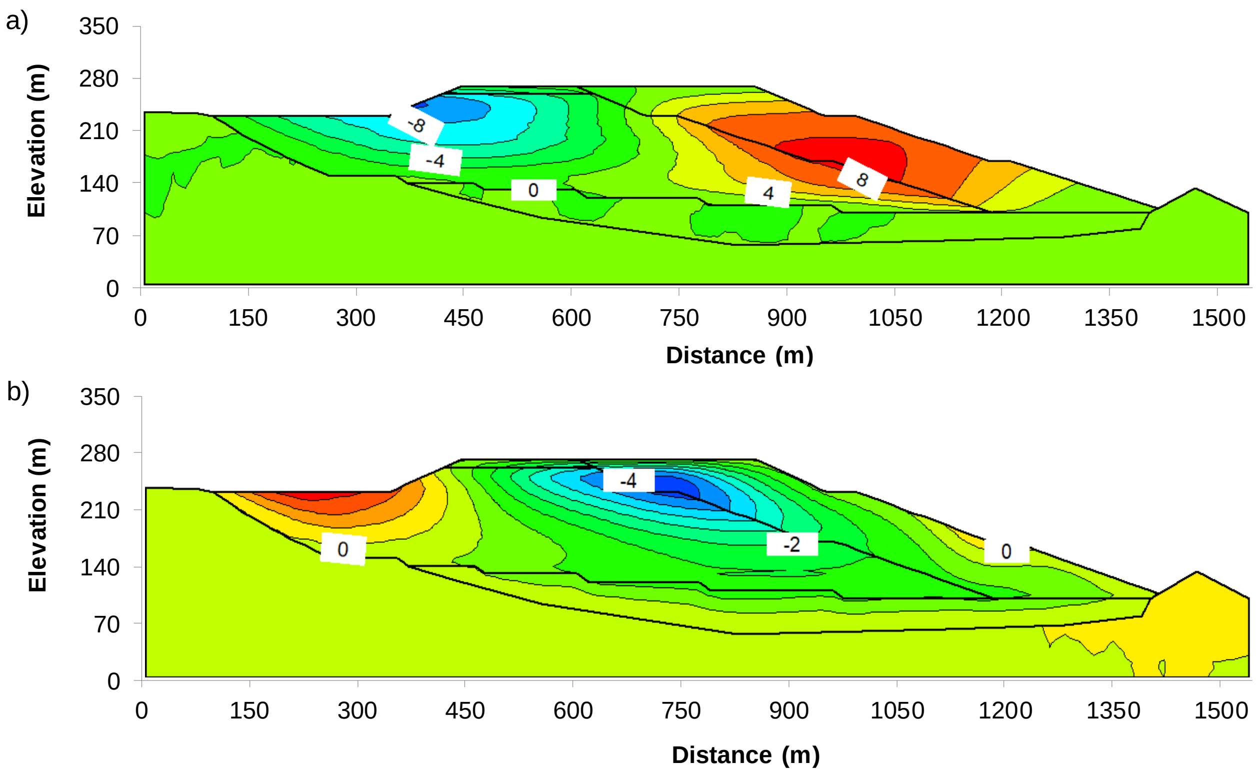

Figure 10: a) horizontal displacements and b) vertical displacements. Case 1.

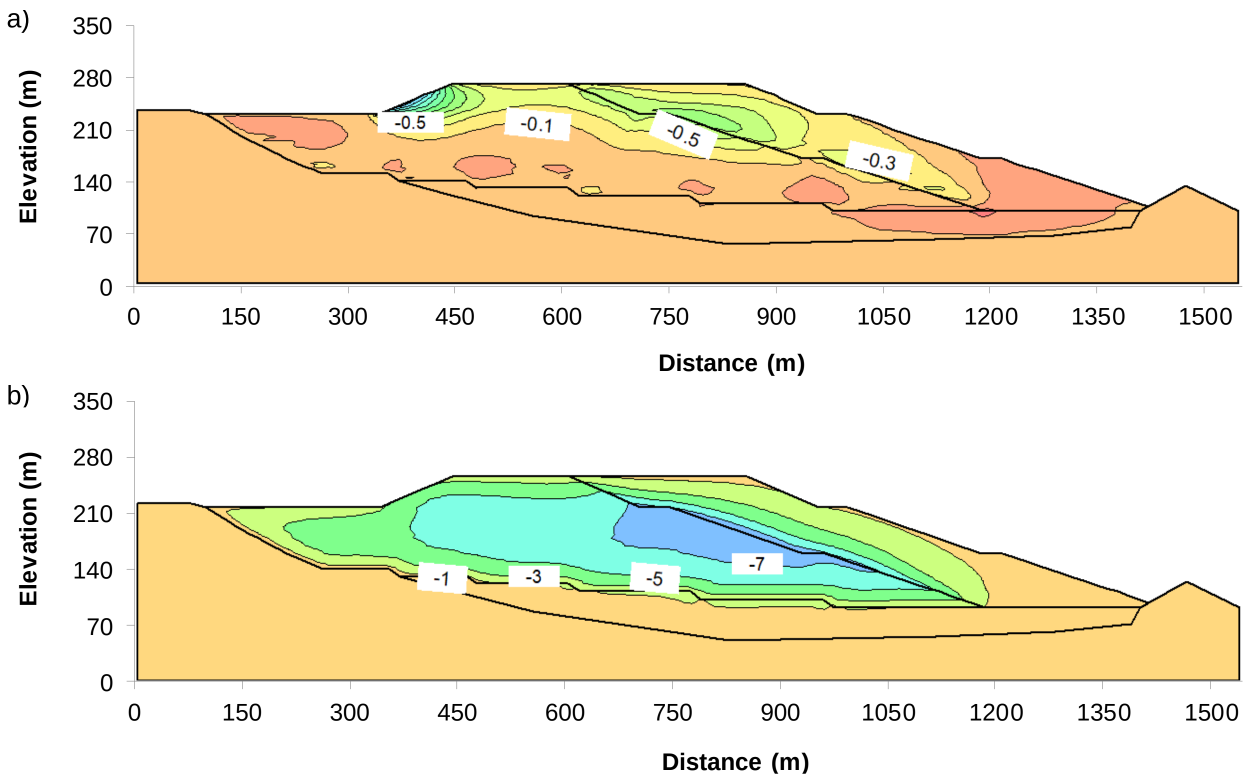

Figure 11: a) horizontal displacements and b) vertical displacements. Case 2

Final limit equilibrium analysis

As a final step, a stability analysis was carried out using the limit equilibrium method (LEM) to complement the performance evaluation previously performed through the numerical analysis. The stability analysis considers the geotechnical parameters shown in Table 3. The post-liquefaction strength of Case 1 Tailings NC-U were estimated from Equation 3 derived from the Norsand model (Jefferies and Been, 2015) when contractive material meets critical state conditions, and based on best practices recommended by Jefferies and Been (2015) considering historical cases. It should be noted that any particle crushing effect due to the maximum loading of the ultimate FTSF configuration, that may influence the shear strength of the uncompacted tailings, has not been considered.

$$\frac{Su_{liq}}{\sigma'_v} = \frac{1+2*K_0}{3} * \frac{M}{2} e^{\frac{-\Psi}{\lambda}} \qquad (3)$$

Table 3. LEM summary parameters

Case	Material	γ (kN/m³)	c (kPa)	ϕ (°)	Sur/σ'	Color
1	Tailings NC-D1	14	0	30	--	
1	Tailings NC-U	14	--	--	Equation 3 and best practice	
2	Tailings NC-D2	14	0	30	--	
All	Tailings C	20	0	35	--	
All	Alluvial deposit	20	0	35	--	
All	Bedrock	26	230	28	--	

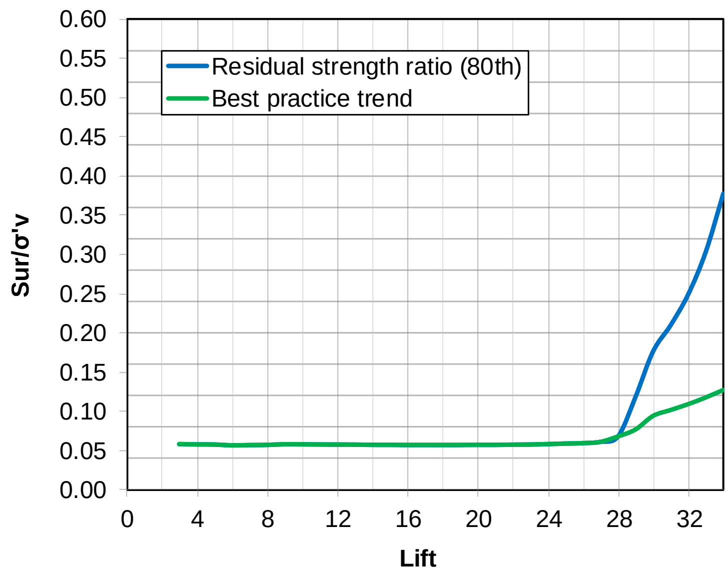

Figure 12: Post-liquefaction strength ratio for contractive uncompacted tailings for Case 1

Figure 12 shows the variation of the post-liquefaction strength which represents the evolution of the 80th percentile of the state parameter at each lift and based on best practices recommended by Jefferies and Been (2015) considering historical cases. It is interesting to note that the two post-liquefaction strength adjustments indicated above are equal up to lift 28, from which point the post-liquefaction strength from historical cases is noticeably lower. The increase in pore water pressure during the FTSF raise was incorporated from the numerical analysis (FEM) for the estimation of the effective vertical stress. For Case 1, a minimum FoS of 1.2 is assumed. For Case 2, the minimum FoS should be 1.5.

Figure 13 shows the limit equilibrium analysis results. As can be observed for Case 1 and Case 2, the FoS are similar up to approximately lift 16 (approximately 80 m high), this is because the failure surface develops only in Tailings C. For Case 1, with the following lifts the failure surface extends towards Tailings NC-U which mostly presents liquefaction condition, which significantly reduces the FoS, reaching the minimum required (FoS=1.2) for lift 24, a further raise causes FoS below the minimum required. For Case 2, the static FoS reach a value of 2.54 for the maximum height of the FTSF.

It is important to mention that to reach at least a FoS=1.2 for Case 1 for the maximum height of the FTSF, it would be required to enlarge the structural zone (Tailings C) to more than 250 m in length, resulting in a more robust configuration. Furthermore, the high values of FoS shown in the stability analyses of Case 2 indicate that the structural zone may eventually be reduced.

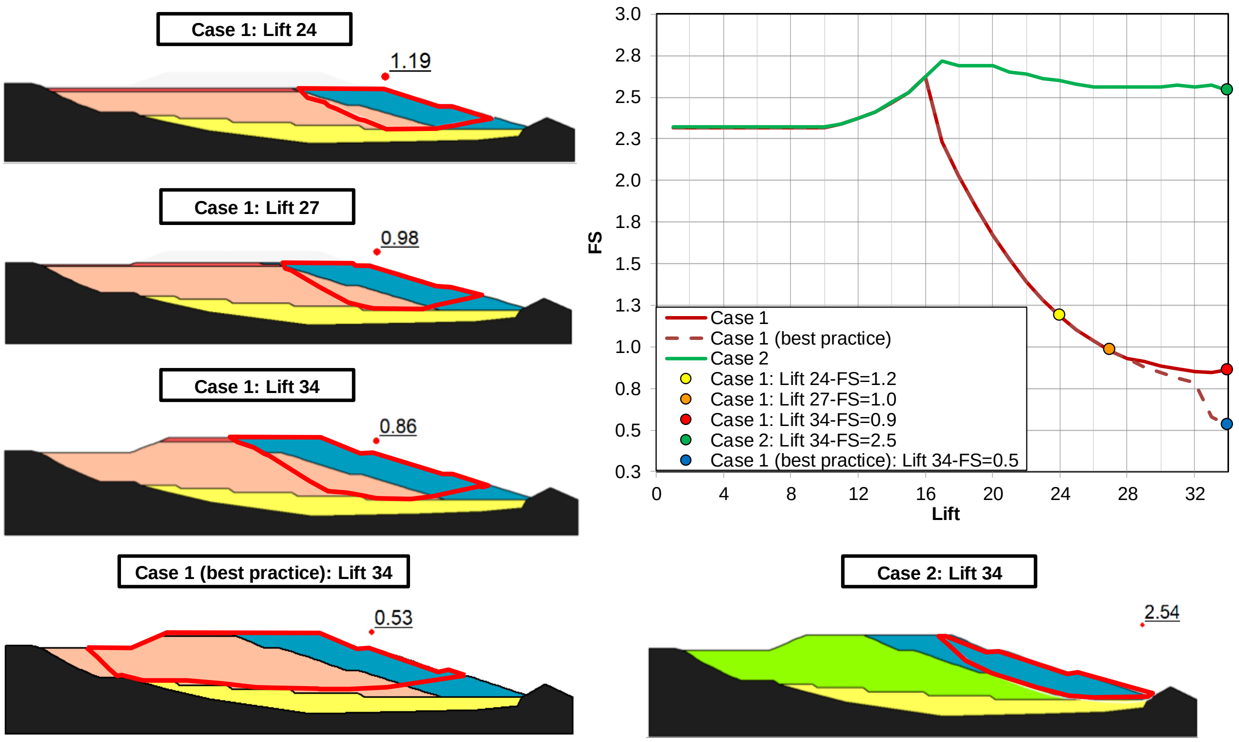

Figure 13: Limit equilibrium analysis results

CONCLUSIONS

Oedometer tests on uncompacted tailings showed that the filtered tailings exhibit a clear trend to more contractive behavior at high moisture content. Therefore, reducing the moisture content either at the filtration plant or by *in situ* aeration will improve the strength of the filtered tailings.

In a FTSF project, the construction of a shell or a structural zone composed of compacted filtered tailings is required, which guarantees the stability of the entire facility, since uncompacted tailings will be placed behind this zone. The structural zone may be sized based on a limit equilibrium analysis considering the most critical conditions of the uncompacted tailings.

Numerical simulation using the Norsand model indicates that for Case 1, the uncompacted filtered tailings with the filtration plant moisture (20%) quickly reach a degree of saturation of 80% for a load equivalent to two lifts (10 m), exhibiting a contractive behavior, generating excess pore pressure and liquefaction from lift 16. However, for Case 2 when the moisture content is equal to the optimum (16%), the initial degree of saturation is very low, not reaching 80% saturation for the maximum height of the FTSF, so there are no excess pore water pressures and therefore, no liquefaction. In both cases, the compacted tailings exhibit a dilative behavior, as expected.

Case 1 corresponds to an undrained scenario where shear strains predominate, while Case 2 represents drained conditions where volumetric conditions will be predominant, which is why horizontal displacements are greater for Case 1 than for Case 2 due to the liquefaction of the uncompacted tailings observed in Case 1, while vertical displacements in Case 2 are greater than in Case 1.

For Case 1, the limit equilibrium analyses show a FoS=1.2 (minimum required) at lift 24, reducing to approximately FoS=0.9 and FoS=0.5 considering Norsand formulation (equation 3) and best practices post-liquefaction strength ratio, respectively, for the maximum height of the FTSF (lift 34). To achieve at least a minimum FoS, the structural zone must be enlarged. For Case 2, the FoS always remains above 2.3, indicating adequate stability conditions.

The results obtained indicate that the procedure presented is suitable for evaluating the performance of a FTSF partially constructed with uncompacted tailings.

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