Tailing Storage Facilities with Cemented Berms for Sustainable Production of Raw Materials

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Abstract This paper presents the geotechnical characterization of a mine iron tailings from Minas Gerais, Brazil, which has revealed liquefaction potential. Toward the deposition of this material in dry stack piles (massive embankments of filtered tailings), a ground improvement solution was studied. The proposed approach is to build structural zones with cemented filtered tailings capable of containing the possible liquefaction failure of the instable material. To avoid the use of Portland cement (OPC) which has a significant carbon footprint, an alternative binder was studied made by the alkaline activation of industrial by-products. To evaluate the efficiency of these berms to contain the eventual liquefaction of the non-stabilized material, limit equilibrium analyses were performed. Analysis with different berm widths and different strength parameters of the cemented material provided the identification of the most favorable design cases.

Keywords Limit equilibrium numerical analysis · Tailings storage facilities · Safety · Alkali-activated binders · Structural berms

1 Introduction

The mining industry is a fundamental pillar of modern society, providing the minerals for energy transition and digitalization. The supply of mineral raw materials requires an adequate management of tailings, the fine material discarded after ore extraction, traditionally disposed in dams raised by tailings hydraulic fill. The increase of tailings dams' accidents (Aznalcollar, Spain—1998, Mount Polley, Canada—2014, Fundao, Brasil—2015, Brumadinho, Brasil—2019) requires an urgent solution to overcome

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this situation of severe consequences: casualties, damages, environmental impacts, and serious disruptions on the raw materials supply.

Loose saturated deposits typical of these dams are very prone to static liquefaction, identified in most of the accidents [4]. Static liquefaction is a consequence of the undrained strength brittleness of tailings in which undrained shearing goes through a peak before attaining critical state conditions at much lower stresses.

The Global Tailings Review has published "Towards Zero Harm: A Compendium of Papers" in conjunction with the Global Industry Standard on Tailings Management, reasserting that innovation in the improvement of tailings management is a crucial aspect [15].

Dry stacking disposal is an alternative to tailings dams where filtered tailings (with less water content) are compacted in massive embankments hundreds of meters high. The term "dry" stack is a misnomer [7], as the degree of saturation (generally 70–85%) depends on filtration process, grain size and type of material, transportation mode or climate conditions. Accidents in these structures during heavy rain periods indicated that more robust solutions are needed in a climate change scenario.

Ground improvement techniques involving high pressures and vibrations are not suitable for these structures as they may trigger liquefaction. Therefore, the solution studied in this work comprised the reinforcement of the dry stack pile with lateral berms made of cemented filtered tailings. These berms improve the stability and avoid the migration of fine particles to the bottom part of the embankment where, due to very high overburden stresses, they tend to be contract when loaded and therefore prone to liquefaction [8].

The use of Portland cement (OPC) in large scale projects is environmentally criticized as its production is highly energy-intensive, it requires a significant amount of natural aggregates, and it is responsible for a large part of world greenhouse gas emissions [12]. For this reason, an alternative binder was studied made by the alkaline activation of industrial by-products. Alkaline activation can be described as a reaction between aluminosilicate materials (precursors) and alkali substances such as sodium (Na) or potassium (K), or an alkaline-earth ion, such as calcium (Ca). This technique is particularly adequate to create binders based on residues, such as fly ash or slag, which constitute very effective options due to their amorphous or vitreous aluminosilicate microstructure [10].

2 Material Characterization

2.1 Iron Tailings

The material used in this paper was Brazilian iron tailings from Minas Gerais. Due to the presence of iron, its particles unit weight (γ_s) is higher than the particles unit weight of natural soils. The grain size distribution is shown in Fig. 1, and its principal parameters in Table 1.

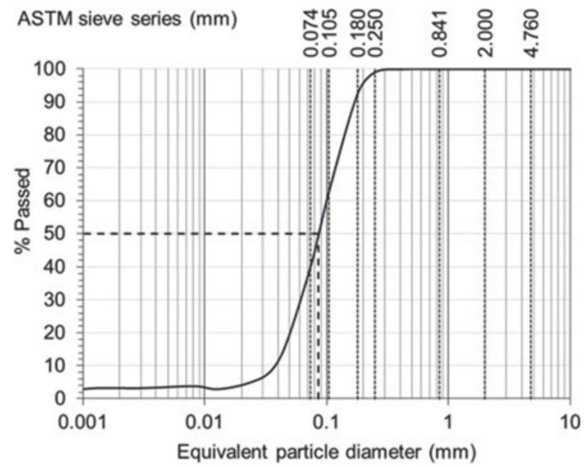

Fig. 1 Grain size distribution

Table 1 Iron tailings parameter

γ_s (kN/m^3)	D_{50} (mm)	C_u	C_c	w_L	w_P
29.51	0.086	2.70	1.01	NP	NP
NP = non plastic					

Critical state soil mechanics offers a useful framework to analyze the liquefaction potential of iron tailings, indicating the states that lead to a contracting behavior [9]. Therefore, triaxial compression tests in loose specimens prepared by very smooth moist tamping were performed to assess the critical state line of the material. The mean effective stresses (*p'*) at the end of consolidation were 50 kPa, 200 kPa, 600 kPa, and 1800 kPa. Figure 2 shows the stress paths of those tests which enabled the identification of the critical state line in the space mean effective stress versus deviatoric stress (*q*). From these results, a *M* parameter equal 1.33 was obtained which corresponds to a critical state friction angle of 33º.

In addition, the same tests were plotted in the space void ratio (*e*) versus mean effective stress (*p'*), so that the CSL can be also defined in this plan (Fig. 3).

These results indicate the location of the states above the CSL that tend to contract upon shear, which correspond to void ratios above 0.85 for low stress levels, or above 0.7 for higher stress levels. Consequently, if the tailings located at the base of the dry stack pile, with high effective stresses acting at such depth, having void ratios above 0.7, they tend to contract during shearing. Therefore, if they become saturated due to heavy rain or inefficient drainage system, they can show liquefaction potential [13].

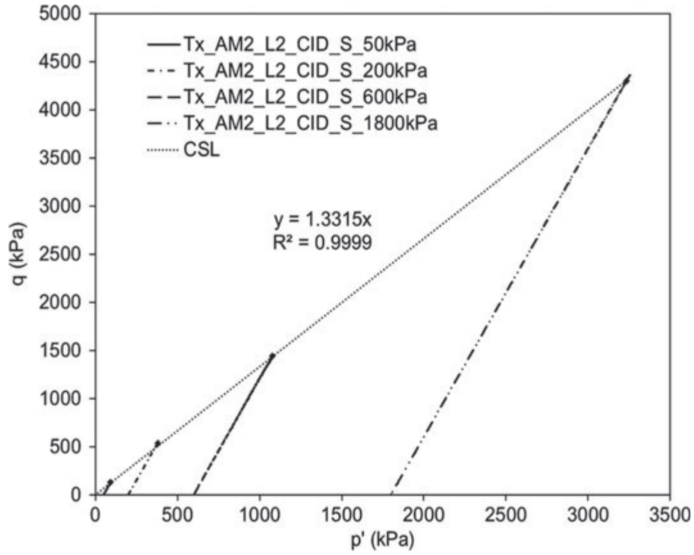

Fig. 2 CSL in the space *p'* versus *q*. *Note* In the test name, the letter "S" indicates loose specimens

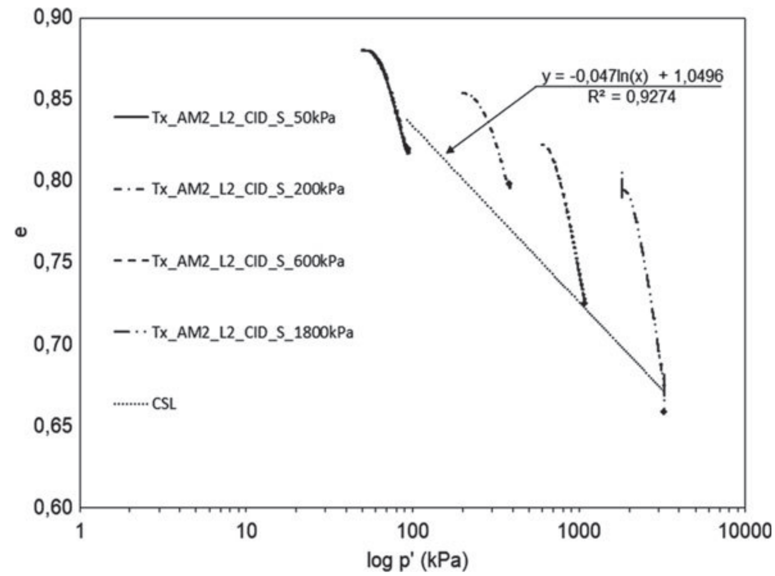

Fig. 3 CSL in the space e versus p'

Table 2 Optimum mixture characteristics

(1) Tailings/Ash	0.30
(2) Liquid content	0.17
(3) SH concentration	11.76 molal

2.2 Ground Improvement Solution

The solution proposed in this work comprises the stabilization of dry stack piles with reinforced berms made by cemented filtered tailings. Note that the compaction of the soils is very difficult due to the high water content of the material obtained in the filtering process. Since Portland cement generates a significant amount of greenhouse gases emissions, an alternative binder was developed. The option was an alkali-activated binder made from industrial wastes such as fly ash. The activation of the fly ash with an alkaline solution generated a binding gel that hardens creating an alkali-activated cement (AAC).

In this work, fly ash type F (with low calcium in its composition) was used as precursor and sodium hydroxide (SH) as activator. Normally, the activator is composed by sodium hydroxide and sodium silicate, but to reduce even more the carbon footprint only sodium hydroxide was used.

The mixture of iron tailings and AAC was optimized using a statistical procedure based on the design of experiments [3]. For this purpose, the following input variables were considered: the weight ratio between iron tailings and ash (1), the liquid content, defined as the weight ratio between the activator and the solids (ash + tailings) (2), and the SH molal concentration (3). Variable 1 ranged between 0.1 and 0.3, variable 2 ranged between 0.16 and 0.22, and variable 3 ranged between 5 and 11.76 molal. The mixtures defined by the statistical method were tested in unconfined compression strength, which was the output variable. The optimum mixture, whose characteristics are given in Table 2, was based on the maximum unconfined compression strength.

Different curing conditions, changing the curing temperature to simulate air temperatures between 20 and 50 °C—and the time of temperature exposure from 24 to 48 h, showed that the unconfined compression strength of this mixture ranges between 100 and 900 kPa at 7 days.

3 Limit Equilibrium Analysis

3.1 Introduction

The stability of filtered tailings stacking is studied using limit equilibrium analysis by Morgenstern Price method with PLAXIS LE v21, with a particular focus on the role of structural berms made from cemented tailings. This study, which focuses on the conceptual evaluation of a 35 m high slope, aims to identify the required

Table 3 Factor of safety (FS) in ANCOLD, CDA, and NBR guidelines

	Normal operating conditions	Uncommon/infrequent conditions (e.g., undrained)
ANCOLD	FS $\geq$ 1.5	FS $\geq$ 1.3
CDA	FS $\geq$ 1.5	FS $\geq$ 1.3
NBR	FS $\geq$ 1.5	FS $\geq$ 1.3

width of the cement tailings perimeter berm, and the necessary cohesion to assure stability. The intent is to satisfy the factor of safety (FS) stipulated by the Canadian Dam Association [6], the Australian National Committee on Large Dams [2], and the Brazilian Association of Technical Standards [1] (Table 3).

Following the elucidation of the properties inherent to the uncemented material, the geometrical configuration of the model is elucidated. Subsequently, the stability of the model, both in the presence and absence of structural berms, is presented for comparison. The objective centers on evaluating the impact of various parameters associated with the cemented material, inclusive of cohesion (c'), unit weight (γ), and friction angle (ϕ'), on the comprehensive stability.

3.2 Material Parameters

The limit equilibrium analysis conducted in this work encompassed three materials as summarized in Table 4: the uncemented filtered tailings; the cemented filtered tailings simulated employing a simple Mohr–Coulomb model utilizing effective stress parameters; and the foundation, which is assumed to be rigid. The filtered tailings below the water table were simulated under undrained conditions, representing the most unfavorable situation. Above the water table, drained conditions were assumed using Mohr–Coulomb parameters.

In the context of the uncemented filtered tailings (Table 5), an undrained strength evolution relative to depth was selected, based on undrained triaxial compression tests. From this, the following relation was obtained for the undrained strength with depth:

$$S_u = 2.87\ z + 19.6 \tag{1}$$

Table 4 Summary of geotechnical parameters used in limit equilibrium analyses

Material	Drainage	Soil type
Filtered tailings with cement	Drained	Mohr–Coulomb
Filtered tailings (below water table)	Undrained	Depth-dependent undrained
Filtered tailings (above water table)	Drained	Mohr–Coulomb
Foundation	–	Bedrock

Table 5 Uncemented filtered tailings parameters

Parameter	Value	Unit
Saturated unit weight (γ_{sat})	20	kN/m^3
Dry unit weight (γ_d)	18	kN/m^3
Undrained resistance at the top of the layer	19.6	kPa
Increase in undrained resistance per meter	2.87	kPa/m
Cohesion (above water table)	2	kPa
Friction angle (above water table)	33.4	

Table 6 Cemented filtered tailings parameters

Parameter	Value	Unit
Dry unit weight (γ_d)	19	kN/m^3
Friction angle (º)	30	º
Cohesion intercept (kPa)	100–300	kPa

In assessing the effective stress parameters of the cemented filtered tailings, the assumption is made that the critical state friction angle of the soil will remain approximately constant (around 30º), while the cohesion intercept would increase due to the cementation process. The range of unconfined compression strengths, identified between 100 and 900 kPa as detailed in Sect. 2.2, allows for derivation of undrained strengths oscillating between 50 and 450 kPa, using the relationship S_u = UCS/2. Considering that the UCS values were obtained at 7 days, a variation of the cohesion intercept between 100 and 300 kPa can be assumed as representative of the strength evolution with time (Table 6). This seems to be in agreement with other results in cemented materials as Rios [11] obtained $\phi' = 30º$ and $c' = 300$ kPa in triaxial compression tests on a cemented silty sand whose UCS was 800 kPa.

3.3 Filtered Tailings Stacking Geometry

The limit equilibrium analysis approach involves representing the foundation as "bedrock," and it stands at a height of 35 m, with tailings slopes inclined at 30° (approximately 1.75H:1.00 V) and outer cement tailings slopes inclined at 28° (approximately 1.90H:1.00 V). These angles have been selected and optimized to maximize tailings containment volumes under hypothetical design conditions. In this analysis, cemented tailings berms with top widths ranging from 5 to 25 m were examined, as shown in the corresponding Fig. 4.

In the limit equilibrium model, an extreme water level condition was considered, in which the water table approaches the apex of the pile. While this scenario may not necessarily reflect actual circumstances, it serves as a useful means to explore situations of maximal instability, which could prove difficult to maintain under stable

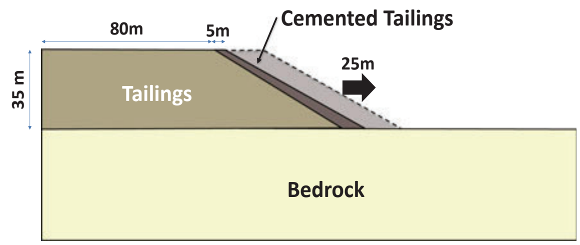

Fig. 4 Analyzed geometry showing a cemented tailings berm with top width ranging from 5 to 25 m

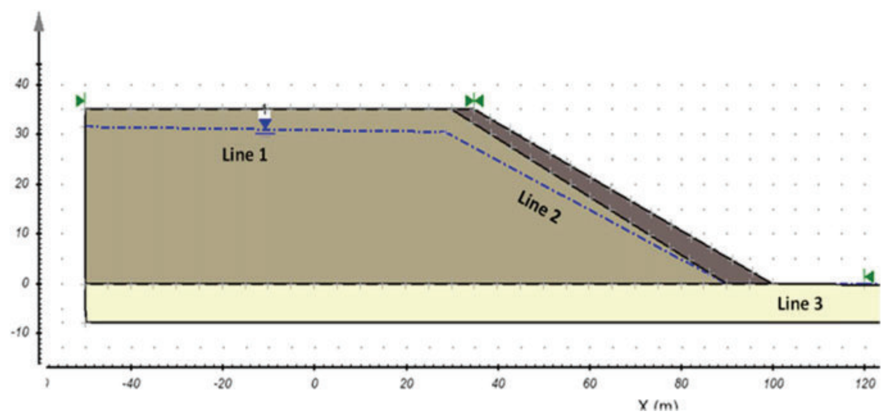

Fig. 5 Piezometric lines considered in the limit equilibrium calculation

conditions. This condition may be a result of an intense rainfall associated to a water flow inside the pile.

The water table is modeled through three piezometric lines: piezometric lines 1, 2, and 3, as indicated in Fig. 5. Piezometric Line 1 begins with an upstream hydraulic head of 31.5 m, which then decreases by 1 m upon reaching the cemented tailings. Beyond this point, Piezometric Line 2 reduces to zero prior to the internal base of the cemented tailings.

3.4 *Filtered Tailings Storage Facility Without a Cemented Tailings Berm*

An initial analysis without a cemented tailings berm was conducted for comparison. This analysis yielded a moment factor of safety of 0.640. The estimated total weight was 1.837 × 104 kN, and the total volume was 9.185 × 102 m^3. The total driving moment was 5.334 × 105 kNm, while the total resisting moment reached 3.414 ×

Table 7 Enhancement of structural safety with cemented tailings berm compared to model without berm

	Berm Width				
	5 m	10 m	15 m	20 m	25 m
FS	0.745	0.798	0.862	0.946	1.048
Δ FSM (%)	+ 16	+ 25	+ 35	+ 48	+ 64

105 kNm. The total driving and resisting forces amounted to 6.377 × 103 kN and 4.025 × 103 kN, respectively.

Although, an undrained strength analysis with such a high water level is a very severe situation, the very low FS obtained indicate that the structure without berms is not stable.

3.5 Perimeter Berm Width Influence

After establishing a baseline without the cemented tailings berm, the study proceeded to analyze five different geometries with cemented tailings berms ranging from 5 to 25 m in width at the top of the structure. In this sensitivity analysis, the cemented tailings were modeled with the lower bound cohesion intercept $c' = 100$ kPa.

Table 7 presents a summary of the FS obtained in each analysis, as well as the % of increase of FS in relation to the model without berm.

Upon conducting the analysis with the different berms, it was observed that among the structures with the most conservative geotechnical parameters, only the structure with a 25-m top width achieved a FS exceeding one (Fig. 6).

3.6 Influence of Cohesion

A sensitivity analysis employing limit equilibrium was undertaken with the objective of investigating the impact of the cohesion (c') parameter, a key geotechnical attribute of cemented tailings deposits, on the stability of a cemented tailings berm of varying top widths.

The outcomes are depicted in Fig. 7, clearly indicating the significant influence that this parameter exerts on the stability of the embankment, as anticipated. According to the Mohr–Coulomb failure criteria used in the Morgenstern price method, the shear strength (τ) is defined as $\tau = c' + \sigma' \tan(\phi')$, where σ' is the effective normal stress on a potential failure plane. This equation clearly illustrates the linear influence of c' and $\tan(\phi')$ on the shear strength, with a notably pronounced influence from the c' component in the Mohr–Coulomb relationship. Since the cemented berm has higher strength than the non-cemented area, the mobilized shear strength on the slip surface

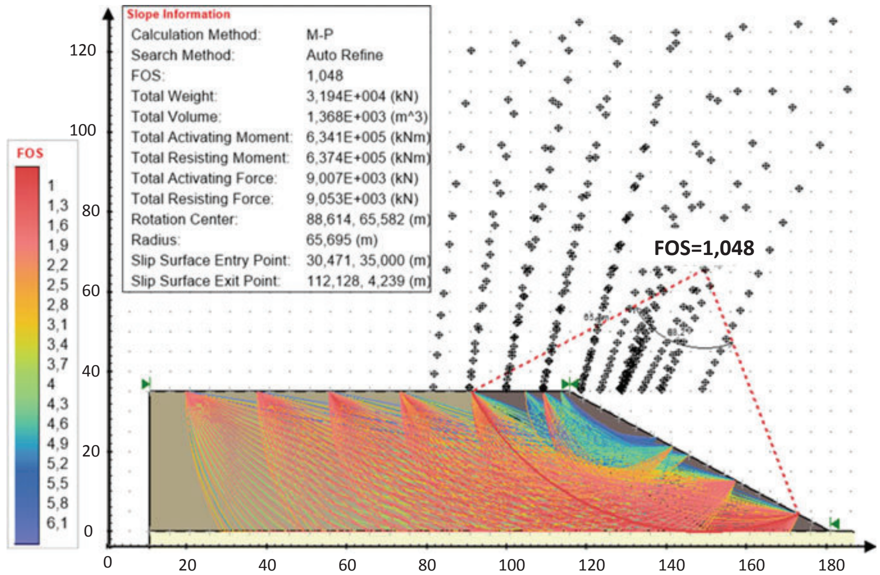

Fig. 6 Limit equilibrium analysis—cemented tailings berms with a 25 m width

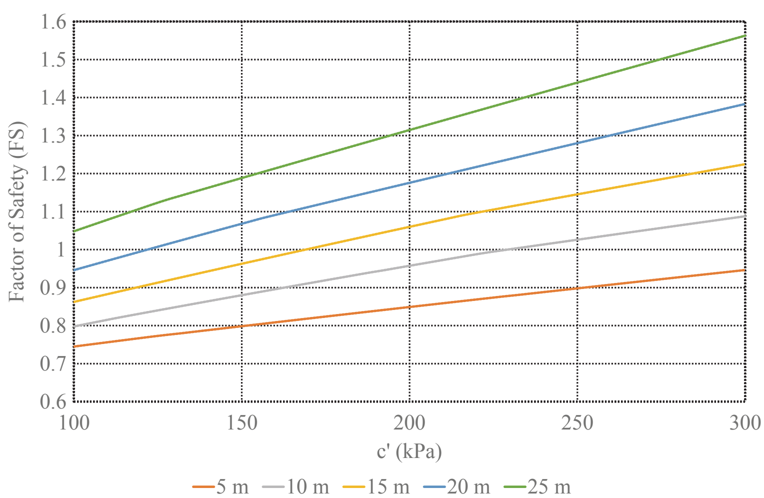

Fig. 7 Relationship between c' and FS

passing on the cemented berm has a significant influence on the overall slope stability and therefore on the obtained factor of safety. This explains an almost linear relation between factor of safety and cohesion (c').

As per Fig. 7, within the limit, equilibrium analysis conducted on a 20 m wide cemented tailings berm with a c' value of 250 kPa, and a 25 m wide cemented tailings berm with a c' value of 200 kPa, the undrained factor of safety (FS) approaches 1.30.

3.7 Influence of Friction Angle and Unit Weight

This section elucidates the influence of the friction angle and the unit weight of the cemented material. A friction angle (ϕ') between 30º and 37º, in alignment with the typical tailings range proposed by Vick [14], alongside a unit weight (γ) ranging from 17.5 to 22 kN/m^3, as recommended by Carneiro [5], were adopted. These ranges are representative of the characteristic values of the iron ore tailings under studied.

The influences of both the friction angle (Fig. 8) and the unit weight (Fig. 9) of the cemented tailings were compared within the context of analyses conducted with a fixed cohesion value of 100 kPa. The observations indicate that the oscillations in unit weight exert a limited influence on the FS as it only concerns a small area of cemented berm. Although the influence of unit weight on the slope stability is minor, it makes sense that an increase in unit weight decreases the factor of safety as the driving shear stresses is inherently a function of the soil's unit weight.

The influence of friction angle is significant, but it has lower impact than cohesion as the shear strength mobilized in the slip surface passing on the cemented berm is proportional to tan(ϕ'). However, both cohesion and friction angle are found to amplify correspondingly with the increase in berm width as the length of the slip surface passing on the cemented berm becomes larger.

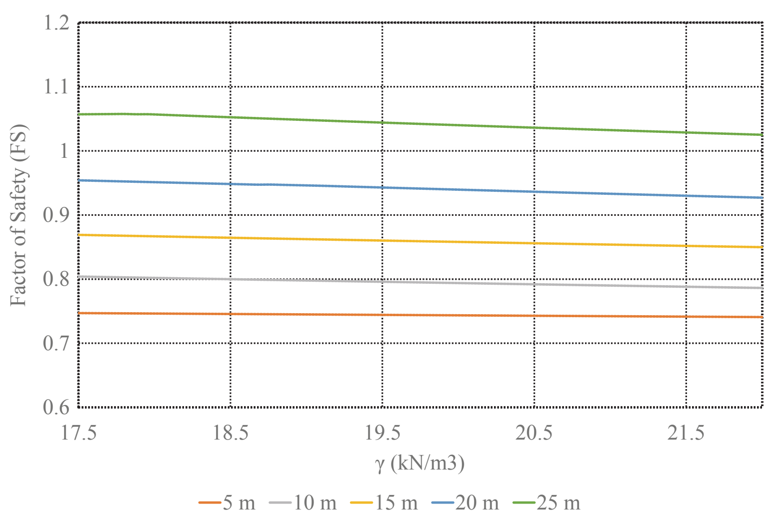

Fig. 8 Relationship between γ and FS

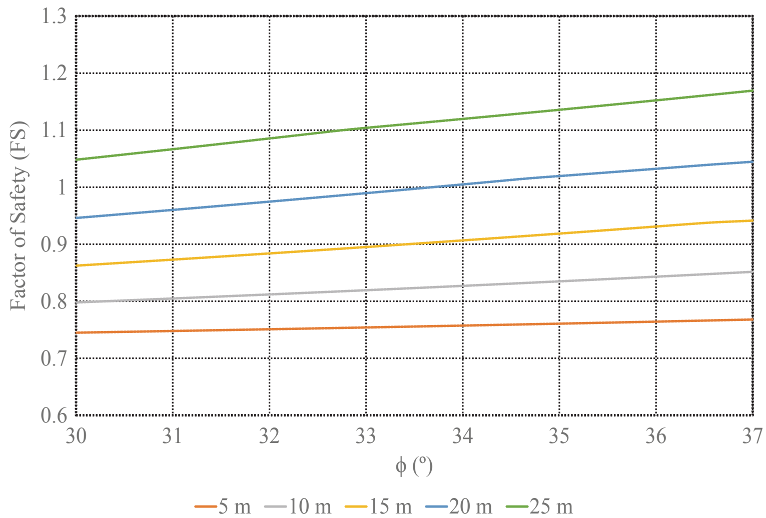

Fig. 9 Relationship between ϕ' and FS

4 Conclusions

This work presents preliminary studies to evaluate the suitability of structural berms made by cemented filtered tailings to improve the stability of tailings dry stacking operations. For this reason, limit equilibrium analysis were developed to do a parametric study to evaluate the influence of berm width, cemented berm strength parameters, and unit weight on the slope stability. Although this parametric study evaluated the influence of each parameter separately, it is possible that its influence on the slope safety factor is inter-related.

These analyses have demonstrated that berms with 25 m of width and a cemented material with $\phi' = 30°$ and $c' = 200$ kPa provide a FS of 1.30 as recommended by technical guidelines for large dams. These strength parameters for the cemented filtered tailings seem to be easily achieved with alternative cements made by the alkali activation of low calcium fly ash, although more studies are necessary. This is very important as this demonstrates that the carbon footprint can be substantially reduced if Portland cement is replaced by more sustainable binders.

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