Stabilization of Filtered Tailings Dry Stacking with Cemented Tailings Berms: A Parametric and Limit Equilibrium Analysis

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Abstract. This work addresses the urgent need for secure and sustainable tailings management, after several Tailings Storage Facility (TSF) failures. This research proposes a stabilization solution for iron ore filtered tailings dry stacking using cemented tailings berms. Despite being a safer alternative to dam deposition, dry-stacked tailings face several vulnerabilities, especially during heavy rainfall or with inadequate drainage systems. For that purpose, limit equilibrium analysis using the Plaxis LE geotechnical software were performed to evaluate the effect of berm width and strength of cemented material, on the stability of these slopes. This process pinpointed the required berm width for a specified dry stacking height and width of cemented tailings, even considering the potential for increased saturation under unfavorable conditions. The conducted analyses aimed to perform a parametric evaluation of the cemented tailings parameters necessary to enhance the structure's stability. The results emphasize the efficacy of the benefits of the computational method in improving the stability and safety of TSFs.

Keywords: “cemented tailings”, “filtered tailings”, “limit equilibrium analysis”, “parametric analysis”, “tailings management”.

1 Introduction

The growing urgency for secure and sustainable tailings management has been fueled by the recent failures of Tailings Storage Facilities (TSFs), like Mount Polley, Canada - 2014; Fundao, Brazil - 2015; Brumadinho, Brazil - 2019. These events led catastrophic environmental and societal repercussions, thereby underscoring the critical need for improved practices in tailings management.

Williams [1] emphasized that, despite the statistical rarity of tailings facility failures, the persistent occurrence of such failures requires a paradigm shift in tailings management. Rather than relying primarily on an economic net present value (NPV) based approach, there's a pressing need to do the transition to a holistic life-cycle perspective. The author advocates the adoption of cutting-edge tailings management technologies and a diverse range of economic models to ensure sustainable outcomes.

Davies [2] emphasized that dry stacking of filtered tailings has pronounced significance in arid regions due to water scarcity and stringent regulations pressing for water conservation. In such settings, reclaiming process water can counterbalance the capital and operational costs linked to tailings management. Building on this, Williams [3] noted that the application of dry stacking isn't confined to arid regions. The method has been effectively applied in regions with wetter and colder climates, with instances like the Greens Creek Metal Mine in Alaska and CSN’s Casa de Pedra Iron Ore Mine in Congonhas, Minas Gerais, Brazil serving as testimonies.

However, dry stacking disposal, despite its advantages, comes with its set of challenges. Davies [3] work, expressed that the term "dry" might be misleading since the saturation level varies significantly due to factors like filtration processes, grain size distribution, and local climatic conditions. Furthermore, Gens [4] added that even though dry-stacked tailings are often considered safer than dam deposition, they aren't devoid of risks. Adverse conditions, such as heavy rainfall combined with inadequately designed drainage systems, can compromise the stability of dry-stacked tailings, sometimes culminating in the liquefaction of the material.

The focus of our investigation is a mitigation strategy that involves bolstering an iron ore filtered tailings dry stack using cemented filtered tailings berms along its boundaries, to reduce the risk of liquefaction. A parametric analysis assessing the stabilization solution for dry stacking of filtered tailings with cemented tailings berms was developed employing Plaxis LE software.

2 Limit Equilibrium Method (LEM)

Duncan & Wright [5] explained that the Limit Equilibrium Method (LEM) is highly regarded in geotechnical engineering for its straightforwardness. This is largely due to the assumption of a failure mechanism that simplifies the calculation of the Factor of Safety (FOS).

In this study the Morgenstern-Price method was used, but methods like Janbu and Spencer are also applicable. Yu et al. [6] stated that while these methods have different assumptions about interslice forces, they typically produce safety factor values that differ by less than 5%. This is the case even if they don't adhere to all global equilibrium conditions. Duncan et al. [7] confirmed that the Morgenstern and Price method adheres to all the essential conditions for static equilibrium.

Duncan et al. [7] also elaborated on the foundational principle behind the Morgenstern and Price (1965) method. It assumes a linear correlation between interslice shear and normal forces, represented mathematically as

$$\mathrm{X} = \lambda f_{(\mathrm{X})} E \tag{1}$$

In this equation, X and E denote the vertical and horizontal forces exerted between slices, respectively. λ embodies a variable scale factor evaluated concurrently with other unidentified parameters, while $f_{(\mathrm{X})}$ signifies a predetermined function distinguished by unique values at each slice boundary.

Duncan [7] provided a comprehensive table (Tab. 1) summarizing assumptions, equilibrium conditions, and unknown variables concerning the Morgenstern-Price method in limit equilibrium procedures.

Table 1. Assumptions, Equilibrium Conditions, and Unknowns in the Morgenstern-Price Method

Assumptions	Equilibrium Equations Satisfied	Unknows Solved
Interslice shear force is related to interslice normal force by Equation (1). The position of the normal force (N) on the base of the slice is typically assumed to be at the center of the base.	– Sum of moments (Σ) about any selected point: n equations; – Sum of forces (Σ) in the horizontal direction: n equations; – Sum of forces (Σ) in the vertical direction: n equations.	– Factor of safety (F): 1 solution; – Interslice force inclination "scaling" factor (λ): 1 solution; – Normal force on the base of slices (N): n solutions; – Horizontal interslice forces (E): n - 1 solutions; – Location of interslice forces (line of thrust): n - 1 solutions.
	Total equations: 3n	Total unknowns: 3n

Duncan et al. [7] noted that the Morgenstern-Price (1965) method traditionally utilized an integration-focused resolution process, enhanced with a modified Newton-Raphson solver. In contrast, modern software applications use a summation method in line with other slice-based techniques. As noted by Bentley [3], the Plaxis LE software uses a "Rapid Solver" solution technique, tailored to compute the safety factor within the Morgenstern-Price framework.

3 Parameters and Assumptions

3.1 Safety Factor Guidelines

According to the Factor of Safety (FoS) requirements stipulated by the CDA [9], the ANCOLD [10], and the ABNT [11] a FoS of 1.5 is required for normal operating conditions and 1.3 for uncommon or infrequent conditions such as undrained circumstances. This uniformity in guidelines across ANCOLD, CDA, and NBR ensures tailings storage facilities stability under diverse scenarios.

3.2 Material parameters

The limit equilibrium analysis was undertaken, accounting for both the iron ore filtered tailings and the cemented iron ore filtered tailings under drained and undrained conditions. Table 2 presents the material parameters for drained conditions. The parameters for the drained conditions of the tailings were based on laboratory tests results thoroughly described by Meneses [12]. The strength parameters for the drained cemented tailings were estimated from Consoli et al [13]. The bedrock, which predominantly comprises the foundation material of this study, was treated as a rigid body in the analyses.

Table 2. Geotechnical Parameters Incorporated for Drained Materials in the Plaxis LE

Material	Strength Type	γ_{dry} (kN/m^3)	γ_{sat} (kN/m^3)	c' (kPa)	ϕ' (º)
Tailings Drained	Mohr Coulomb	18.0	20.0	2.00	33.4
Cemented tailings	Mohr Coulomb	18.0	19.0	50.00	30.0

Meneses [12] reported that the filtered tailings under undrained conditions produced an Undrained Strength Ratio of 0.28. For the cemented filtered tailings, a comprehensive spectrum of unconfined compressive strengths (UCS) was postulated, ranging from 100 to 1000 kPa. By adopting the relationship Cu = UCS/2, these compressive strengths translate to undrained shear strengths (Cu) spanning between 50 and 500 kPa. This extensive range acknowledges the temporal evolution of cemented materials and the potential for varying degrees of cementation. Consequently, short-term strength (e.g., after 7 days of curing) may exhibits undrained shear strengths from 45 to 250 kPa. In contrast, long-term strength (e.g., after 28 days of curing) may manifest undrained shear strengths ranging from 150 to 500 kPa. The geotechnical parameters adopted for undrained materials in the Plaxis LE analysis are detailed in Table 3.

Table 3. Geotechnical Parameters Incorporated for Undrained Materials in the Plaxis LE

Material	Strength Type	γ_{sat} (kN/m^3)	Cu (kPa)	Cu/ σ'_{v0}
Tailings	Undrained Strength Ratio	20.0	-	0.28
Tailings with Cement (7 days)	Undrained Strength Constant	19.0	45 (initial) 45-250	-
Tailings with Cement (28 days)	Undrained Strength Constant	19.0	150 (initial) 150-500	-

3.3 Filtered Tailings stacking geometry

The geometry used for the sensitive limit equilibrium analysis features a 35-meter-high stack of filtered tailings placed over a bedrock foundation. This stack is encapsulated at the perimeter by cemented tailings, which have a width varying between 5 and 25 meters. The internal slope of the tailings stack follows a slope ratio of 1.75H:1.00V. On the other hand, the external slopes of the cemented tailings conform to a slope ratio of 1.90H:1.00V. This intentional variation in slope ratios is designed to maximize the storage capacity for the filtered tailings under different design conditions, while concurrently minimizing the footprint of the cemented tailings.

In assessing stability, the equilibrium model considers a critical scenario where the phreatic surface ascends nearly to the tailings stack's peak. This is not a direct representation of actual conditions but a hypothetical scenario to explore maximum instability situations, such as significant rainfall events causing heightened hydraulic activity within the tailings stack. Three piezometric lines define the phreatic surface. Piezometric Line 1 starts with an upstream hydraulic head of 31.5 m, dropping by 1 m at the cemented tailings, and Piezometric Line 2 further reduces to zero at the cemented tailings' internal base. The model also examines cemented tailings berms with top widths ranging from 5m to 25m (Fig. 1).

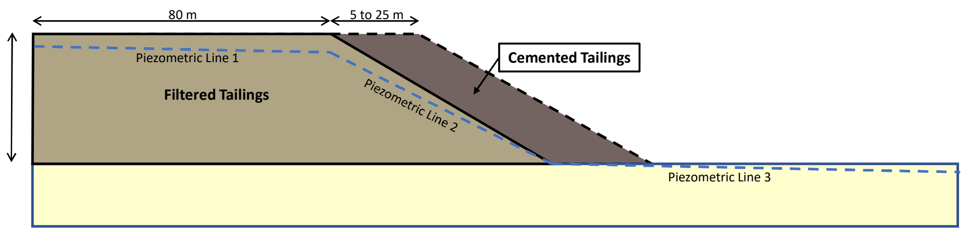

Figure 1: Geometry of Cemented Tailings Berm (5m-25m) & Piezometric Lines in the LEM analysis.

4 Results

4.1 Drained and Undrained LEM Analysis of Filtered Tailings stacking without a Cemented Berm

For a comparative assessment, the structure was initially evaluated without the incorporation of a cemented tailings berm. In this configuration, the derived Factor of Safety (FoS) values were 0.854 under drained conditions and 0.640 under undrained conditions, as depicted in Fig.2. These metrics fall short of the established industry benchmarks (FoS=1.5 for drained and FoS=1.3 for undrained), signaling potential stability challenges.

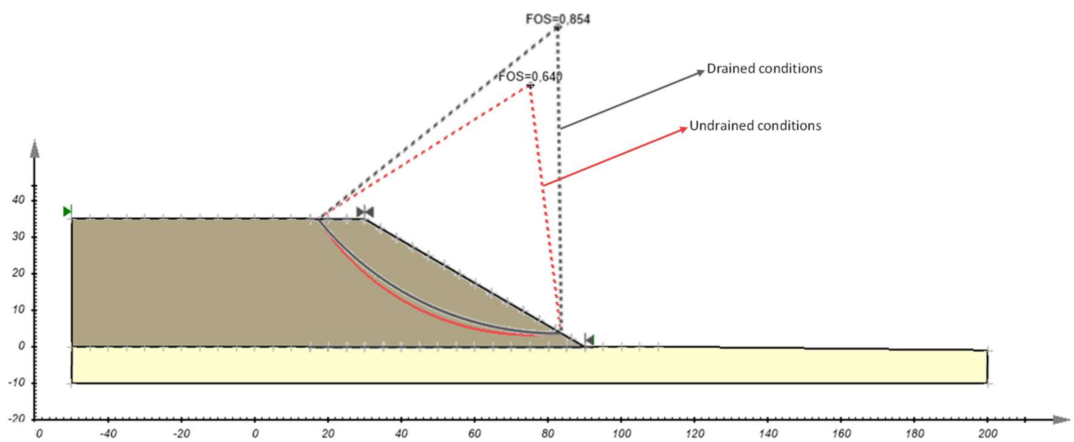

Figure 2. Comparative Analysis of the FoS Under Drained and Undrained Conditions Without Cemented Berm

4.2 Perimeter Berm width Influence

A series of analyses were conducted for both fully drained and undrained materials to evaluate the efficiency of implementing the cemented tailings berm, using the parameters indicated on Table 2 and 3, respectively. In all analyses, the water table level remained consistent. To systematically assess the influence of berm width on the structural stability of cemented tailings berms, various geometrical configurations were examined. These configurations encompassed a spectrum of berm top widths, ranging from 5m to 25m. The sensitivity assessment was grounded in a conservative methodology, establishing an undrained shear strength (Cu) of 45 kPa for short-term strength cemented tailings and 150 kPa for long-term strength cemented tailings.

Table 4 presents the Factor of Safety (FoS) for each configuration under both drained and undrained conditions and compares the FoS enhancement against a baseline without a berm. For drained conditions, a berm with 15 m already meets the required FoS of 1.5. However, no configurations met the stability criteria under undrained conditions for the given shear strength values on the short term. Figures 3 and 4 further illustrate results for the 25m-wide berm in both short-term and long-term scenarios.

Table 4 – Comparative Analysis of Structural Stability: The Impact of Cemented Tailings Berm Width

	BERM WIDTH				
	5 m	10 m	15 m	20 m	25 m
FoS Drained	1.341	1.463	1.739	1.895	2.037
FoS Undrained (short-term strength)	1.085 (-19%)	0.106 (-24%)	1.115 (-31%)	1.127 (-41%)	1.155 (-43%)
FoS Undrained (long-term strength)	1.185 (-12%)	1.161 (-21%)	1.193 (-31%)	1.229 (-35%)	1.293 (-37%)
% Δ FoS Relative to Bermless Model (Unrained) (short-term strength)	+70%	+73%	+74%	+76%	+80%
% Δ FoS Relative to Bermless Model (Unrained) (long-term strength)	+85%	+81%	+86%	+92%	+102%

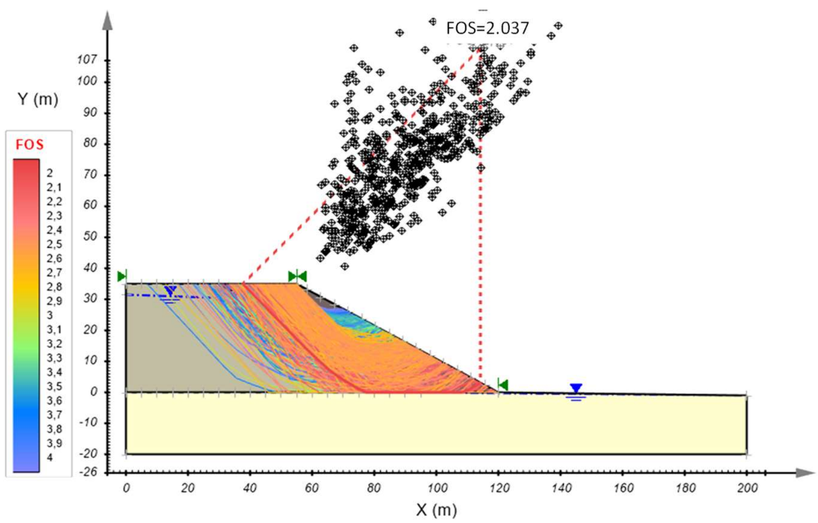

Figure 3. LEM Analysis - Cemented Tailings Berm with 25m width (Drained Conditions)

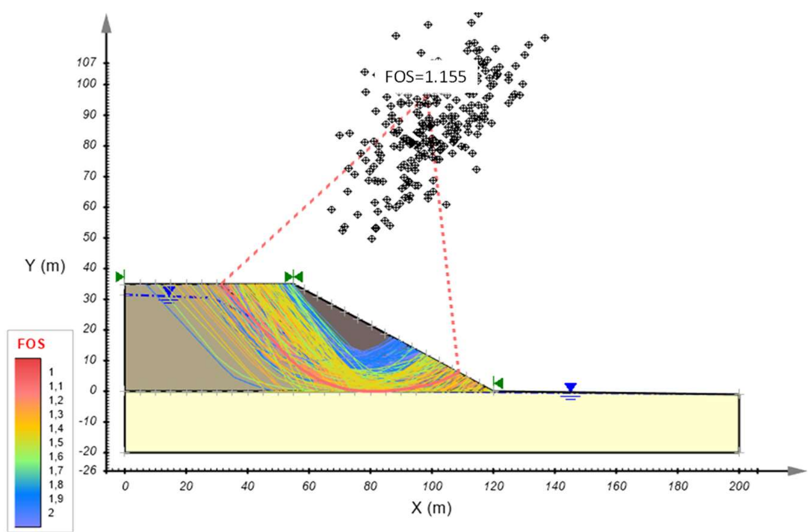

Figure 4. LEM Analysis - Cemented Tailings Berm with 25m width (Undrained – short term strength)

4.3 Influence of Undrained Shear Strength

In geotechnical evaluations, the undrained shear strength (Cu) stands out as an essential parameter influencing stability of tailings deposits in undrained conditions. To provide a comprehensive understanding of its significance, Figure 5 presents the findings, emphasizing the importance of the Cu parameter in the stability of the embankment when using the parameters indicated in Table 3. In this case, instead of considering a single undrained strength for short or long term conditions, the whole spam of values were analyzed.

Considering the Tresca failure criterion, the mobilized shear strength is equal to the undrained strength of the soil. On the other hand, given the superior strength of the cemented material in contrast to its non-cemented counterpart, the undrained shear strength mobilized along a potential slip surface within the cemented berm emerges as a decisive element in the holistic slope stability assessment having a pronounced influence on the resultant factor of safety. Such insights accentuate the near-linear interrelation between the factor of safety and Cu observed in Figure 5. Moreover, as the berm width increases, the part of the potential slip surface within the cemented berm becomes higher. This enhances the influence of the undrained strength of the cemented berm on the overall factor of safety, which is clear on Figure 5 as the slope of the relation between FoS and Cu increases with berm width.

As illustrated in Figure 5, a limit equilibrium appraisal of a 20m-wide cemented tailings berm characterized by a Cu value of 250 kPa, or a slope with a 25m-wide berm at a Cu value of 200 kPa, provide the required undrained Factor of Safety (FoS) of 1.30.

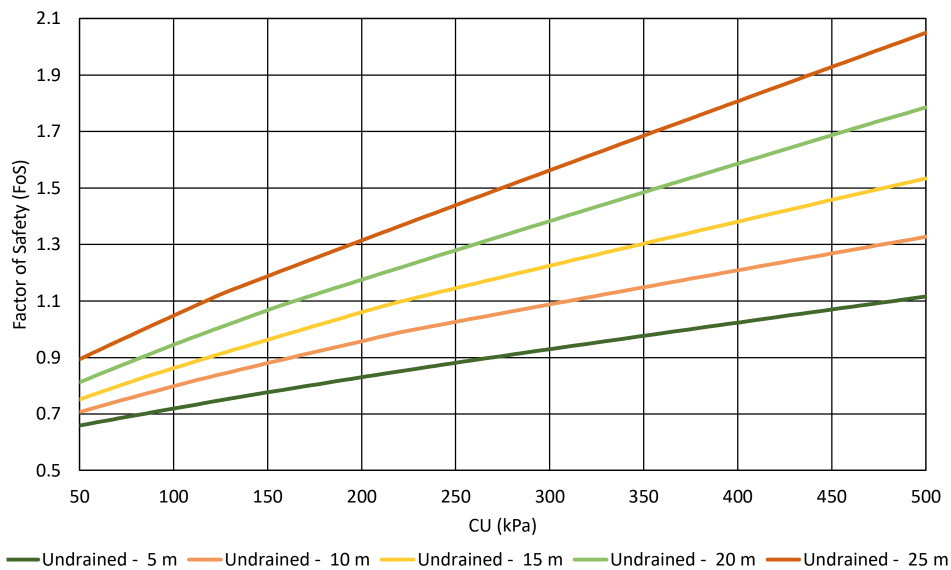

Figure 5. Relationship between undrained strength of cemented berm and FS

5 Conclusions

The comprehensive geotechnical investigation presented in this study underscores the intricated interplay between key parameters and their influence on the stability of cemented tailings berms. This research systematically demonstrated the influence of berm width and essential geotechnical properties, including undrained shear strength.

A relationship emerged between berm width and the Factor of Safety (FoS) as a larger berm width increased the FoS. Specifically, a 15m-wide berm exhibited the required FoS value under drained conditions (higher than 1.5), setting a preliminary benchmark for stability considerations. However, achieving stability under undrained conditions remains a challenge, underscoring the imperative for augmented geotechnical attributes or design refinements.

The undrained shear strength, a key geotechnical parameter, was pinpointed as determinant in the stability equation of cemented tailings berms in undrained conditions. Elevated values of undrained shear strength corresponded to FoS values nearing acceptable thresholds under undrained conditions (higher than 1.3). Notably, the study revealed a near-linear relationship between undrained shear strength of the cemented material and overall slope stability FoS, reinforcing the paramount importance of this parameter in stability assessments.

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