Comparative Analysis of the Effect of Disposal in Tailings and Waste Rock Piles

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Abstract. The disposal of tailings currently represents a major challenge in the Brazilian mining scenario. As a result of the accidents that have occurred in the last decade, the legislation has become increasingly demanding with regard to the disposal processes of these materials. Therefore, new disposal systems are being researched and studied to ensure safer, functional and efficient procedures. One of the strategies currently being evaluated is the implementation of piles with mixed disposal of tailings and waste rock. This study aims to compare the numerical modeling of two alternatives for mixed disposal systems in piles. The first considered an interlayer disposal of tailings and waste rock in an layered co-mingling system, and the second considered a homogeneous mixture of tailings (50%) and waste rock (50%) in a co-disposal system.

The material characterization and geotechnical parameters were obtained from laboratory tests. To understand the stress-strain behavior, finite element analyses were performed using RS2 software. Additionally, limit equilibrium analyses were performed with SLIDE 2 to evaluate the stability of each system. The results obtained did not show significant differences between the two disposal systems, presenting similar safety factors, as well as deformations and displacements in the same order of magnitude. The studies performed show the opportunity to implement interleaved systems for tailings disposal as well as the need to conduct more detailed studies that evaluate more critical considerations in the structure.

Keywords: Tailings · Waste rocks · Piles · Codisposal · FEM · Limit equilibrium

1 Introduction

Mining is one of the most important economic activities in Brazil and represents approximately 4% of the country's gross domestic product. Mineral exploration is a set of activities that allow the extraction of mineral goods from nature for use in manufactures used by humans. According to Silva (2014), this process comprises three general stages. The first is the mining stage, where waste rock materials are removed to gain access to the ore. The second stage is beneficiation, where the ore receives treatments aimed at separating it from elements considered secondary or contaminants, usually discarded as tailings. The beneficiation operations can include simple mechanical processes such

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as crushing, washing and granulometric classification. The last stage is the use of the product or material of interest and its commercialization.

In this process, one of the main challenges is the final disposal of materials that have no economic value, such as tailings and waste rock, which for now are disposed of in piles and dams, respectively. As highlighted in the abstract of this paper, due to recent accidents with dams, companies have sought alternatives for the disposal of tailings generated in their complexes, and one of these alternatives would be the disposal of the tailings in the form of a pile. However, given its characteristics, disposal in piles can condition the structure to risks of undesirable geotechnical events, such as liquefaction. In this sense, developing alternative techniques for the disposal of mining waste in a sustainable way has been and will be a major challenge of the mining sector. Thus, the disposal of dewatered tailings in piles has become a necessary alternative, in view of the exhaustion of the accumulation capacity of dams and to provide better conditions in terms of safety and environmental aspects. Furthermore, technological advances in the ore processing area allow the water contained in the tailings pulp to be removed, thus making their disposal in piles feasible.

In this way, a viable alternative would be to integrate these disposal systems in the same deposit through the disposal of tailings and waste rocks in the same physical space. When the tailings-waste rocks mixture is previously performed or performed in the disposal environment itself, we have the technique defined as co-disposal (Homogeneous mixtures). On the other hand, when the waste rock materials are disposed in the same physical space, without, however, needing to mix them, we have the technique defined by shared disposal, as is the case of layered co-mingling (Wickland et al, 2006; Peixoto, 2012).

The present study consists of an analysis and comparison of performance between waste rock and tailings disposal systems, evaluated from numerical models to simulate stability and stress-strain behavior. The systems to be compared are layered co-mingling pile and co-disposal with homogeneous mixture pile.

2 Methodology

Hypothetical geological-geotechnical pile models were proposed for the disposal of tailings from the iron ore beneficiation process. For this modeling a symmetric geometry was adopted from the central axis of the structure, considering 100 m wide at the crest and 100 m high, raised sequentially with symmetric trapezoidal waste berms with 10 m of free height, 10 m wide at the upper base and slope of 34 degrees inclination in relation to the horizontal axis (1.5H 1.0V). Additionally, an altered rock mass foundation was considered for the structure and the maximum water level with a height of 40 m inside the pile, this hypothetical geometry adopted is presented in Fig. 1. For the evaluation and comparison of disposal performance, two models were proposed. In model 1, the disposal was performed intercalated with 1-m-thick waste rock layers and 1-m-thick tailings layers, simulating a layered co-mingling system. In model 2, a homogeneous mixture of material was considered, composed of 50% waste rock and 50% tailings, simulating a co-disposal system. For the analyses performed in the sequence, the behavior of the materials was considered as drained.

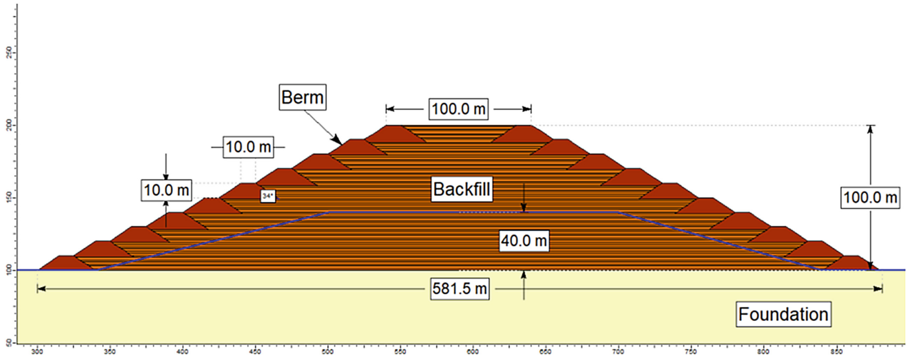


Fig. 1. Hypothetical Pile Geometry

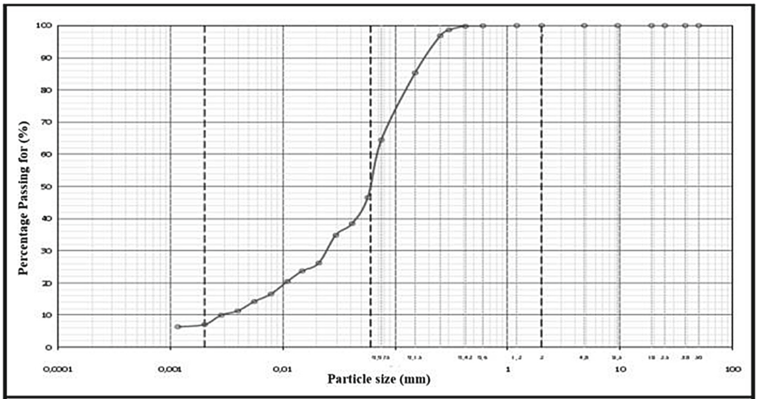
2.1 Material Properties

The characterization of the materials adopted in the proposed models was obtained from laboratory test results and literature references. The laboratory tests were performed according to Brazilian standards, mainly following the indications of ABNT NBR 6457, NBR 7180, NBR 7181 and NBR 7182 (2016).

For the foundation, an altered phyllite was designed, a rock group common in the iron ore beneficiation region in the state of Minas Gerais. The adopted parameters were estimated from parameters found in database and literature for phyllite among them Lopes et al. (2007), therefore, it was decided to adopt a cohesion value of 100 kPa and friction angle of 28°. The deformability parameters were adopted from the literature, specifically Look (2007).

The tailings studied have around 20% iron oxides, with the rest also consisting mostly of silicates and aluminosilicates. The material has an non-homogeneous particle size distribution, characterized as a silty sand, specifically, with 50.3% in the sand fraction, 42.7% in the silt fraction and 7.0% in the clay fraction, as shown in Fig. 2. The tailings have a specific weight of 3.47 g/cm^3. While consistency limits, the samples did not present liquidity or plasticity limits, i.e., the materials and their mixtures do not have or it is not possible to determine their plastic behavior limits. From normal proctor tests, the compaction characteristics of the material were determined, being these, 12.7% of optimum moisture, 2.0 g/cm^3 of dry specific weight and 2.25 g/cm^3 of wet specific weight. To determine the strength parameters, triaxial compression tests were performed in a drained consolidated condition for 5 specimens at confining stresses of 125 kPa, 250 kPa, 500 kPa, 750 kPa, and 1000 kPa. The results, as illustrated in Fig. 3, presented an effective cohesion of 1.2 kPa and a friction of 31.5°. The deformability parameters were adopted from the literature, specifically Look (2007).

The waste rock adopted in the study consists mainly of silicates and aluminosilicates, from the amphibole, mica, and feldspar groups. After being crushed to a 10mm aperture, for grain size adequacy to the geotechnical tests, they were characterized by sieving and sedimentation. They are mostly in the gravel fraction, corresponding to 75.0% of the mass, with 20.2% in the sand fraction, 3.8% in the silt fraction, and only 1.0% in the clay fraction. This is a monomodal particle distribution, but of coarse particle size, as shown



CLAY (%)	SILT (%)	SAND (%)			BOULDER (%)
		FINE	MEDIUM	COARSE	
7	42,7	41,3	8,9	0,1	0

Fig. 2. Particle Size Tailings

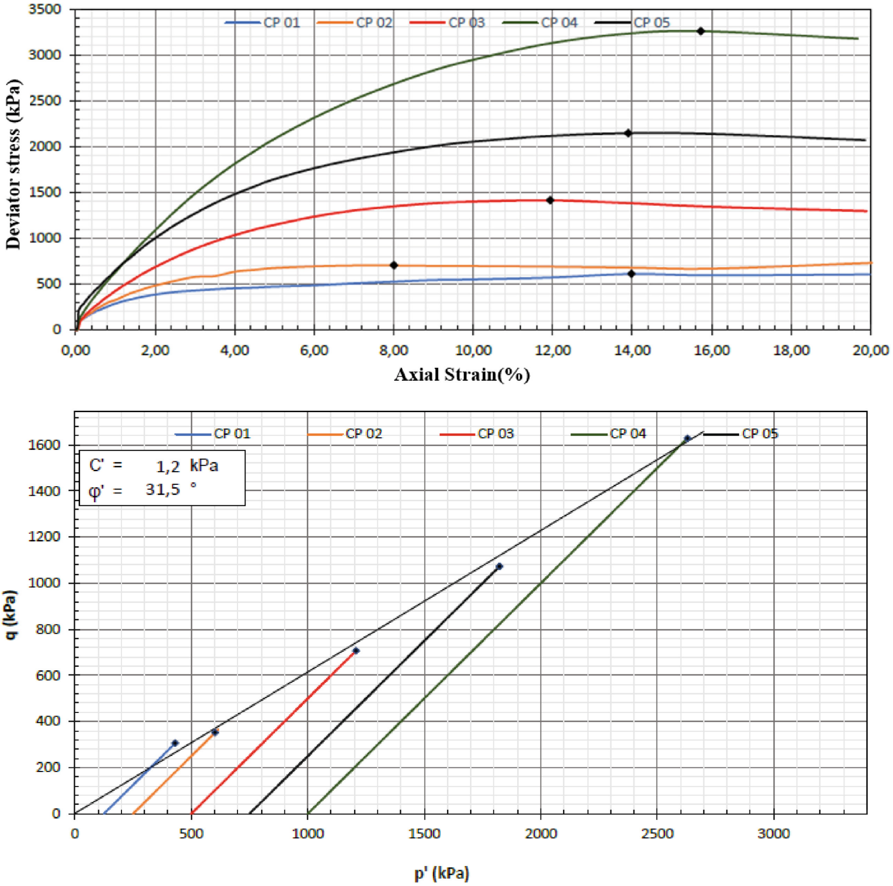
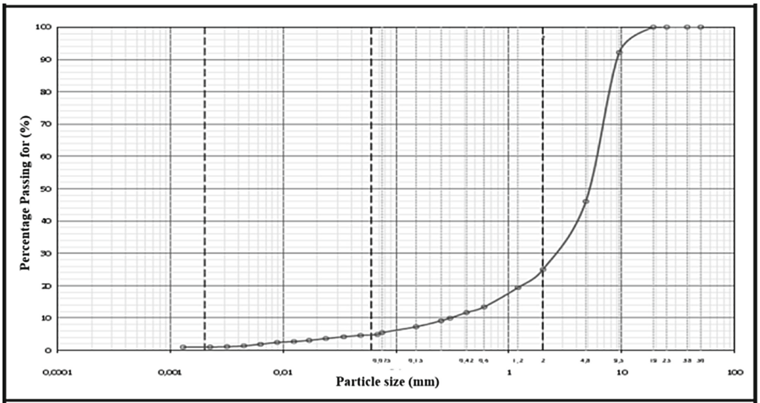


Fig. 3. Triaxial Test Tailings



CLAY (%)	SILT (%)	SAND (%)			BOULDER (%)
		FINE	MEDIUM	COARSE	
1	3,8	3,4	5,2	11,6	75

Fig. 4. Particle Size Waste Rock

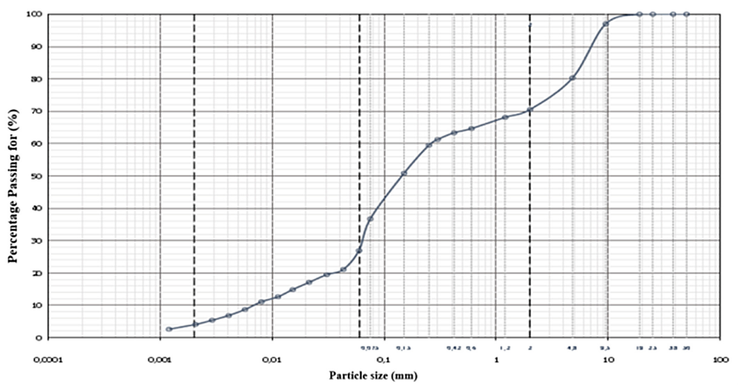
in Fig. 4. The crushed waste rock has a specific weight of 3.02 g/cm^3. As consistency limits, the samples did not present liquidity or plasticity limits. As resistance parameters, a 35° friction angle and zero cohesion were adopted, values usually used for waste rock. The deformability parameters were adopted from the literature, specifically Look (2007).

The mixed material, a product of the composition of 50% tailings and 50% waste rock, resulted in a particle size composition of 29.5% gravel, with 43.2% sand, 23.3% silt and 4.0% clay, as shown in Fig. 5. The homogeneous mixture has a specific weight of 3.36 g/cm^3. As consistency limits, the samples did not present liquidity or plasticity limits. From proctor tests, the compaction characteristics of the material were determined, being these 8.3% of optimum moisture 2.20 g/cm^3 of dry specific weight and 2.25 g/cm^3 of wet specific weight. To determine the strength parameters, triaxial compression tests were performed in drained condition for 4 specimens at confining stresses of 125 kPa, 250 kPa, 500 kPa, and 1000 kPa. The results, as illustrated in Fig. 6, presented an effective cohesion of 46.6 kPa and a friction of 30.9°. The deformability parameters were adopted from the literature, specifically Look (2007).

Therefore, based on the results of laboratory investigations and literature values, the properties of the materials inserted in the proposed models were defined as shown in Table 1.

2.2 Stability Analysis

To evaluate the safety in the final condition of the waste rock and tailings pile disposal work, stability analyses were performed using three methods of analysis, based on the Limit Equilibrium theory: Bishop Simplified, Morgenstern-Price and Spencer by using the computer program for two-dimensional studies Slide2®, developed by Rocscience. In these analyses were sought circular surfaces (homogeneous massif) and non-circular potential rupture, in search of the lowest factor of safety (FoS).



CLAY (%)	SILT (%)	SAND (%)			BOULDER (%)
		FINE	MEDIUM	COARSE	
4,0	23,3	27,8	9,5	5,9	29,5

Fig. 5. Particle Size Homogeneous mixture

According to Gerscovich (2016) the rupture surface tends to be circular in relatively homogeneous soils, and may have a flatter appearance in the occurrence of a more significant anisotropy in relation to strength. The planar or translational surfaces, on the other hand, are characterized by discontinuities or planes of weaknesses. And finally, the mixed form ruptures occur when there is heterogeneity, characterized by the presence of materials or discontinuities with lower strengths.

Thus, non-circular analyses were considered at the global rupture surface level, due to intercalations of materials, which may result in a plane of weakness. At the local level, the ruptures present themselves within the same soil layer (homogeneous massif), thus tending toward a circular rupture surface.

To perform the stability analyses, two basic scenarios were adopted that refer to the position of the water level inside the structure and the foundation. The first is the static scenario, considering the adoption of the water table of the operational condition. The second scenario is the pseudo-static analysis, considering the same conditions for defining the water table of the operational scenario, under seismic loading effects, for this condition, the inclusion of additional static forces was considered, representing the inertial force components generated by dynamic loading.

The horizontal seismic coefficient (Kh) used in the pseudo-static stability analyses was adopted as being equal to 50% of the PGA, as recommended by several authors (Corps of Engineers, 1982; Marcuson and Franklin, 1983; Hynes-Griffin and Franklin, 1984; among others). Although the use of a value for the vertical seismic coefficient Kv is a widespread concept, Seed and Martin (1966), and Duncan and Wright (2005) suggest that the vertical seismic coefficient be adopted equal to 0, under the assumption that the motion of seismic shear waves is vertical. Papadimitriou et al. (2014), in turn, reinforces that the values of vertical accelerations in regions of low seismic activity can be considered negligible or of low relevance.

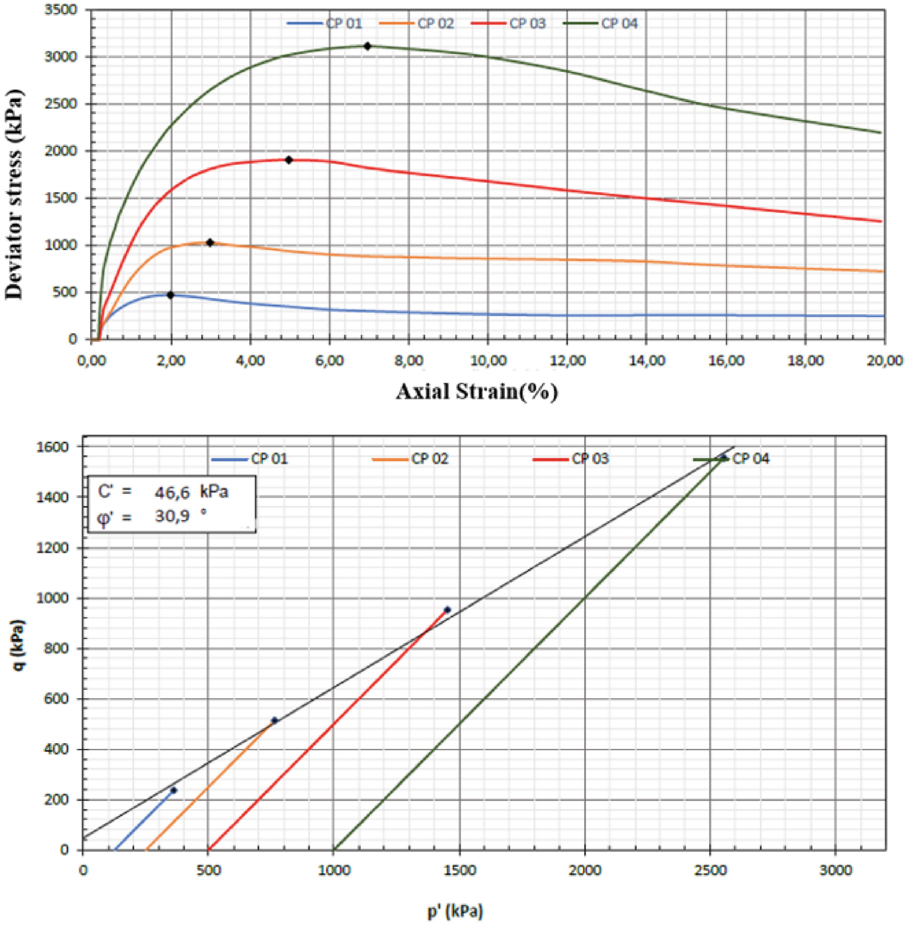


Fig. 6. Triaxial Test Homogeneous mixture

Table 1. Material Properties

Material	**Unit weight (kN/m^3)**	**Cohesion (kPa)**	**Angle of internal Friction (º)**	**Young's modulus (MPa)**	**Poisson's Ratio**
Foundation	20,0	100,0	28,0	200,0	0,3
Tailings	22,0	1,2	31,5	6,0	0,3
Waste Rock	20,0	5,0	35,0	50,0	0,3
Homogeneous mixture (50/50)	21,0	46,6	30,9	28,0	0,3

To obtain the seismic acceleration value, the map with a return time (TR) of 2,475 years was considered. The studies presented by Assumpção et al. (2016), present peak accelerations in rock - PGA rock, it is emphasized that this study should be used on a preliminary basis, and in the later design phases should take into account effects of amplification/wave attenuation, focal distance of the earthquake and the like. The Environmental Guide of the Ministry of Mines and Energy of Peru (MINEM -1997), points out that seismic accelerations in soil material, for the same focal distance, are between 46% and 65% higher compared to accelerations in rock material.

In this manner, in this preliminary design stage, it was considered that the project is inserted in a zone with maximum acceleration of 0.16 g. Therefore, the value adopted for the horizontal seismic acceleration coefficient (Kh) in the pseudo-static analyses was equal to 0.08 g.

In all analysis sections, local and global surfaces with the lowest safety factor were sought, according to the guidelines of the Brazilian regulatory standards ABNT NBR 13.029/2017 and ANM Resolution Number 95 of 2022.

2.3 Stress-Strain Analysis

The stress-strain studies were carried out for the previously mentioned models. The modeling was done in the plane-strain condition, with field stresses generated by gravity and consideration of the real soil surface, using the finite element analysis software RS2 developed by Rocscience. During the modeling of the stress-strain analysis, the generation of pore pressure was not evaluated, because the analysis seeks to identify the displacements and strains generated by the pile construction.

The boundary conditions set in the simulation problem were x and y displacement constraint for the rocky boundary and x displacement constraint for the sides of the model. While the water table of the structure was a maximum level of 40 m inside the structure. All materials were considered as plastics with Mohr Coulomb failure criterion.

The stages evaluated considered the progressive elevation of the pile during its construction. In summary the modeling steps consider:

- Current condition: establishing the behavior reference of the structure.
- Stage 1: Initial stage, referring to the natural terrain without pile implantation.
- Stage 2 to Stage 11: referring to the elevation of the stage left berm and right berm and internal disposal of the tailings and waste rock.

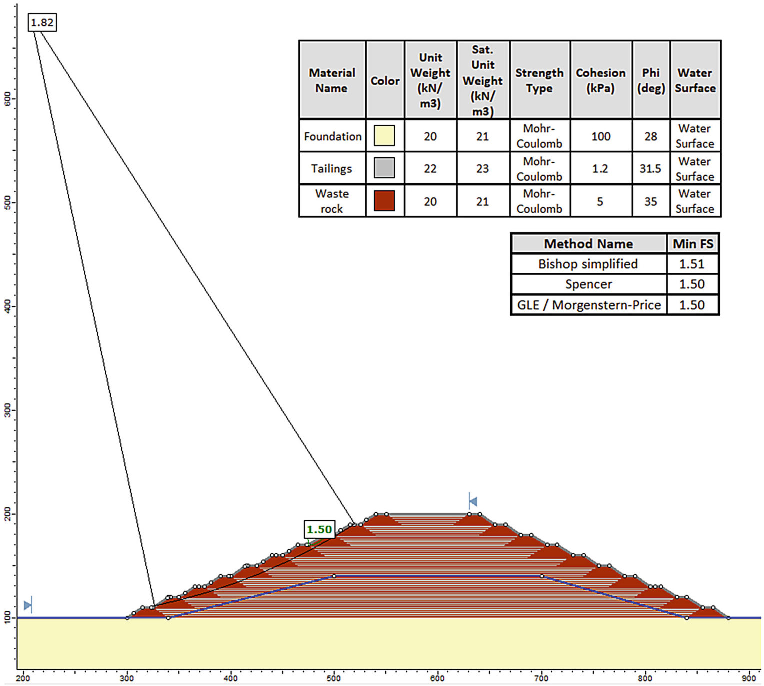
3 Results

3.1 Stability Analysis

The results of the stability analyses obtained are presented in Table 2. Local ruptures were evidenced at the berms of the pile and global ruptures intersecting the overall structure. As a result, the factor of safety values for the proposed static and pseudo-static conditions do not represent significant variations when comparing model 1 and model 2. The global and local factors satisfy the criteria determined by the consulted regulations.

Table 2. Factor of Safety Results

Factor of Safety	Static Circular *FoS min: 1,5*	Static Non-Circular *FoS min: 1,5*	Pseudo-static Circular *FoS min: 1,1*	Pseudo-static Non-Circular *FoS min: 1,1*
Model 1 *Layered co-mingling*	Global: 1,82 Local: 1,50	Global: 1,86 –	Global: 1,47 Local: 1,29	Global: 1,50 –
Model 2 *Homogeneous Mixture*	Global: 1,80 Local: 1,50	Global: 1,84 –	Global: 1,45 –	Global: 1,48 –

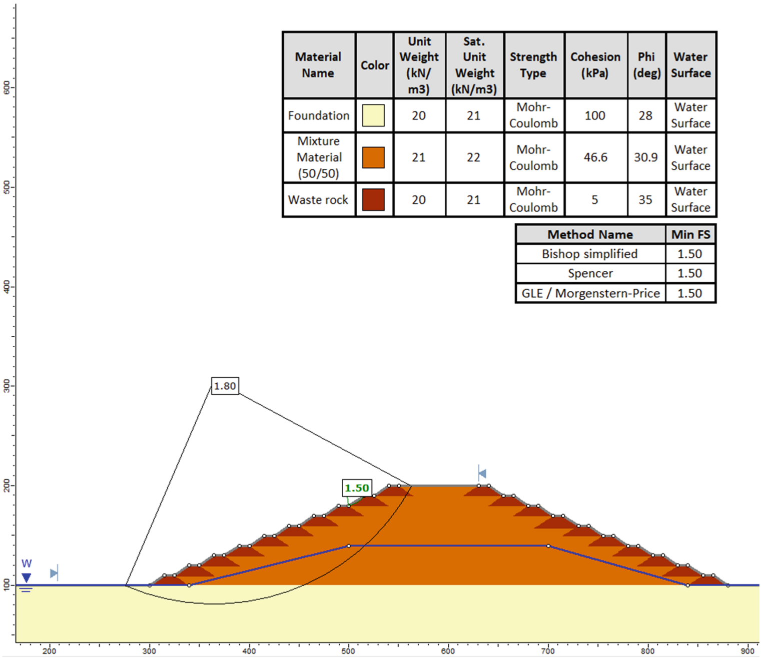


Material Name	Color	Unit Weight (kN/m3)	Sat. Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
Foundation	🟨	20	21	Mohr-Coulomb	100	28	Water Surface
Tailings	⬜	22	23	Mohr-Coulomb	1.2	31.5	Water Surface
Waste rock	🟥	20	21	Mohr-Coulomb	5	35	Water Surface

Method Name	Min FS
Bishop simplified	1.51
Spencer	1.50
GLE / Morgenstern-Price	1.50

Fig. 7. Stability Analysis Model 1 – Static Condition Circular Surface.

Regarding the shape of the rupture wedge, model 1 generally presented global ruptures at the lateral sides of the structure, crossing the alignment of the elevated berms. The general behavior of the model is illustrated in Fig. 7. Model 2, on the other side, presented global ruptures passing near the central axis of the structure and intersecting the foundation. The general behavior of the model is illustrated in Fig. 8.



Material Name	Color	Unit Weight (kN/ m3)	Sat. Unit Weight (kN/m3)	Strength Type	Cohesion (kPa)	Phi (deg)	Water Surface
Foundation	🟨	20	21	Mohr-Coulomb	100	28	Water Surface
Mixture Material (50/50)	🟧	21	22	Mohr-Coulomb	46.6	30.9	Water Surface
Waste rock	🟥	20	21	Mohr-Coulomb	5	35	Water Surface

Method Name	Min FS
Bishop simplified	1.50
Spencer	1.50
GLE / Morgenstern-Price	1.50

Fig. 8. Stability Analysis Model 2 – Static Condition Circular Surface.

3.2 Stress-Strain Analysis

The results of the stress-strain analyses using the finite element method were obtained for model 1 and model 2. The results will be analyzed here after the total elevation of the structure, i.e., the results obtained for the last construction stage (stage 11). The total displacement results are illustrated in Fig. 9, where it is shown a higher concentration of displacements in model 1, at the top of the structure, while at the bottom, the models show similar behavior.

In order to get a better interpretation of the progression of displacements along the height of the structure, the total displacements along the lateral and central lines presented in Fig. 9 were plotted. The results obtained show that model 1 presents greater displacements when compared to model 2. The results of the axes mentioned above are illustrated in Fig. 10. In the lateral axis, the total displacements of model 1 were up to 66% larger than the displacements in model 2. In the central axis, the displacements of model 1 were up to 80% larger than the displacements in model 2. In both measurements, the displacements increased proportionally with the height of the structure.

The total displacements at the top of the structure and at the contact between the structure and the foundation were also analyzed, as presented in Fig. 11. The shape of the displacement curves was similar for both models. At the top of the structure, the largest total displacement is evidenced in the central axis of the structure. Model 1 shows displacements of up to 180% when compared to model 2. At the contact between the structure and the foundation, the displacement behavior is practically the same.

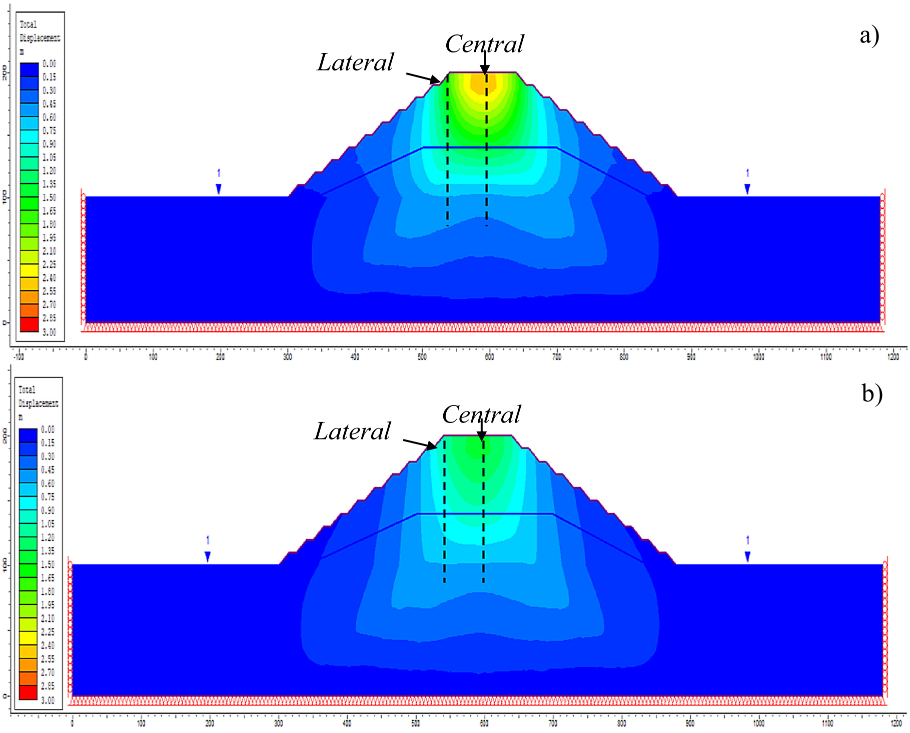


Fig. 9. Total displacements - a) Model 1 and b) Model 2

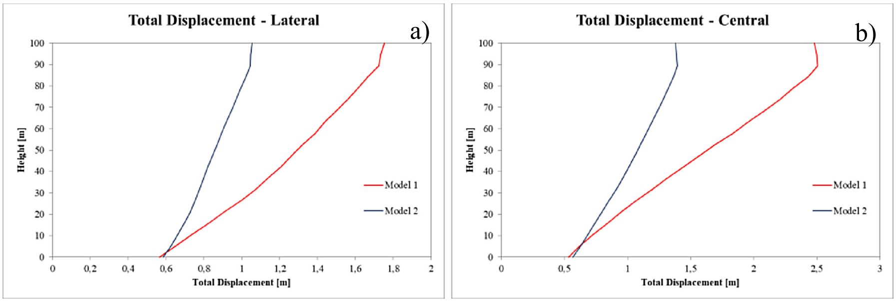


Fig. 10. Total displacements - along the height of the structure - a) Lateral and b) Central

The state of yielding in the structures was analyzed in Figure 12, presents the concentration of yielding in the foundation and in the structure. For both models the concentration of yielding has a similar behavior, being more intense at the base, and decreasing with height. As for the pile body, in model 1 the concentration of the plasticized elements is more intense near the contact with the foundation, in the upper third of the structure, and at the top of the structure. In model 2, the concentration intensifies in the lower half of the structure, presenting concentration also at the top.

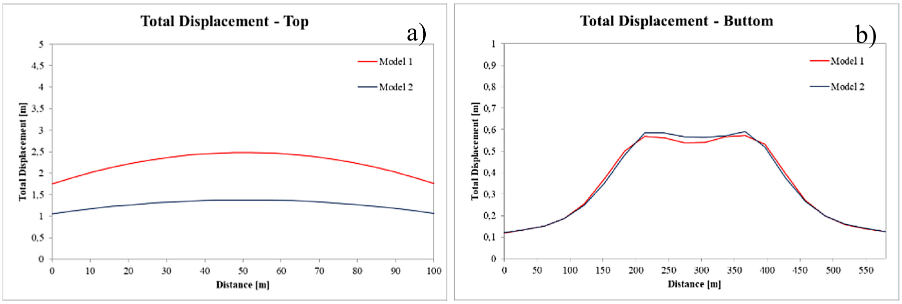


Fig. 11. Total displacements a) top and b) button structure-foundation contact

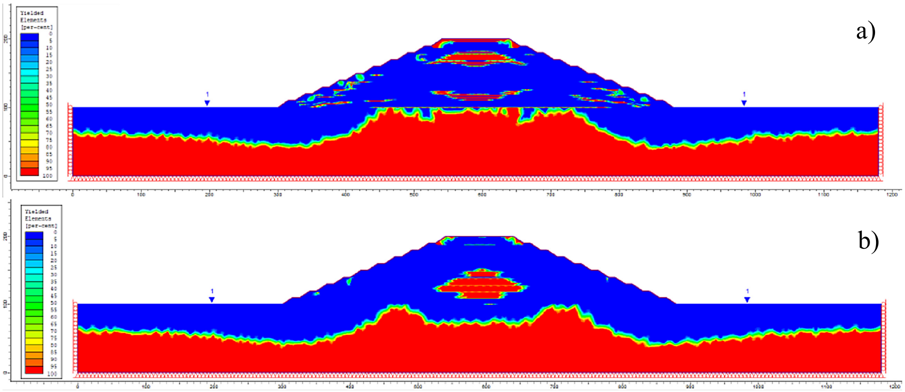


Fig. 12. Yielded elements a) Model 1 and b) Model 2

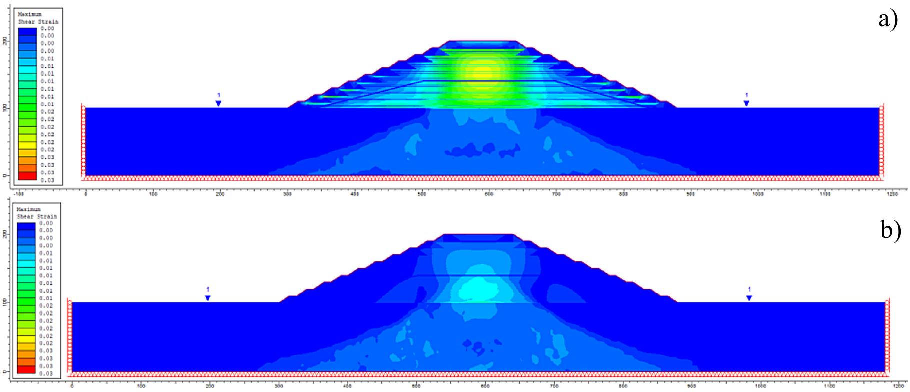


Fig. 13. Maximum shear strain a) Model 1 and b) Model 2

Finally, the distribution of the maximum shear strain is shown in Fig. 13. The models present the largest strains in the central axis of the structure. In model 1, maximum strains close to 2% are evidenced, while in model 2, the maximum strains are close to 1%.

4 Conclusions

This paper presented the studies performed for waste rock and tailings disposal by modeling conceptual pile methods. Model 1 considered a layered co-mingling pile system, while model 2 considered a homogeneous mixture pile system. The main conclusions are presented below.

- According to laboratory results, it is evidenced that the mixture of tailings and waste rocks improves the behavior of the disposed material, increasing the resistance parameters, generating a better performance in structures with homogeneous disposition, additionally preferential layers that can generate planes of weakness in the structure are avoided.
- The simulated disposal models presented factors of safety that satisfy the minimum values required for stability analyses.
- Model 1 showed higher factors of safety than model 2, with rupture surfaces through the alignment of raised berms, while model 2 showed more centralized surfaces with intersection at the foundation.
- The highest total displacement of model 1 is on the order of 2.5% of the structure height, while in model 2, the highest displacement is on the order of 1.4% of the structure height.
- Model 1 presents the lowest performance regarding displacements, with values of up to 80% more compared to model 2.
- The models presented almost the same level of shear strain, around 1 to 2%.
- Model 1 presents the yield zone in the central region of the base of the structure, while model 2 presents the smallest yield zones, along the top of the structure.
- A change in the behavior of the structure is identified, with yielding only at the top in model 1, and yielding at the base in model 2, which leads us to understand that the excess pore pressure is dissipated during the construction process, where the waste rock bands constitute horizontal drains, allowing a drained behavior of the structure.
- Considering the assumptions adopted, the models satisfy the conceptual conditions for a confined pile disposal system.

For future research and feasibility of the proposed systems, it is recommended to study the effect of the undrained condition of the materials, evaluation of the optimum humidity of the disposal, constructability and operation aspects, the effect of seasonality on the water table of the structure, internal drainage system, permeability influence and other topics that may be relevant to the performance of the disposal systems and that were not covered in this study.

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