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The effect of waste rock inclusions on the slope stability of tailings dikes

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ABSTRACT
Mining operations generate two primary types of solid waste: waste rock and tailings. The coarse-grained waste rock extracted to access the ore zones is usually disposed in piles on the surface. The fine-grained tailings produced by the ore milling process are generally transported hydraulically to a surface impoundment confined by retaining dikes. The design of such impoundment raises various geotechnical issues, including the risk of instability of the dikes along the external slope. Previous work has shown that waste rock inclusions (WRI) can be used to improve the hydro-geotechnical response of tailings impoundments. This method consists in placing waste rock inside the impoundment to improve drainage and reinforce the retaining system. In this paper, calculations are conducted to assess the effect of WRI on the stability of tailings impoundments under static loading conditions. The calculations results, which can serve to analyze the behavior during and after tailings slurry deposition in the impoundment, illustrate how WRI may be used to enhance the factor of safety of the retaining dikes.

RÉSUMÉ
Les opérations minières génèrent deux principaux types de rejet solide: les stériles et les résidus miniers. Les roches stériles à granulométrie grossière, extraites pour accéder aux zones minéralisées, sont généralement placées dans des haldes en surface. Les résidus à grains fins produits par le traitement du minerai sont usuellement déposés hydrauliquement dans des parcs à résidus miniers confinés par des digues de retenue. La conception de ces ouvrages de retenue pose divers défis géotechniques, incluant ceux liés aux risques d'instabilité de la pente externe. Des travaux antérieurs ont montré que les inclusions de roches stériles (IRS) peuvent aider à améliorer la réponse géotechnique des parcs à résidus. Cette méthode consiste à placer des stériles à l'intérieur du parc pour améliorer le drainage et renforcer le système de retenue. Dans cet article, on présente les résultats de calculs pour illustrer l'effet des inclusions sur la stabilité des digues en conditions statiques. Ces calculs, qui peuvent servir à analyser le comportement des ouvrages pendant et après le dépôt de résidus, illustrent comment l'utilisation d'IRS peut aider à augmenter le facteur de sécurité des digues.

1 INTRODUCTION

The stability of tailings impoundments remains a major challenge for the mining industry, as demonstrated by numerous failures reported in recent years (e.g. Davies et al. 2002; Aubertin et al. 2002b; Azam and Li, 2010; Roche et al. 2017; Strachan and Caldwell 2018; Santamarina et al. 2019). Such events, which often lead to uncontrolled tailings flow following a breach, can have devastating impacts on local communities and ecosystems.

The risk of geotechnical instability of an impoundment can be reduced by adding waste rock inclusions (WRI) that are stronger, stiffer and more permeable than the tailings. Recent work has shown that WRI improves the geotechnical and environmental performance of impoundments by providing accelerated drainage during and after tailings deposition and by adding reinforcement against static and seismic loads (Aubertin et al. 2002a, 2011, 2019; James and Aubertin 2010, 2012; L. Bolduc and Aubertin 2014; Jahanbakhshzadeh et al. 2019). Placing waste rock inclusions inside an impoundment is also giving more flexibility for tailings management by forming compartments (or cells) that help optimise slurry deposition (Figure 1), as demonstrated at the Canadian Malartic mine (QC, Canada) where the technique has been used for many years (James et al. 2017).

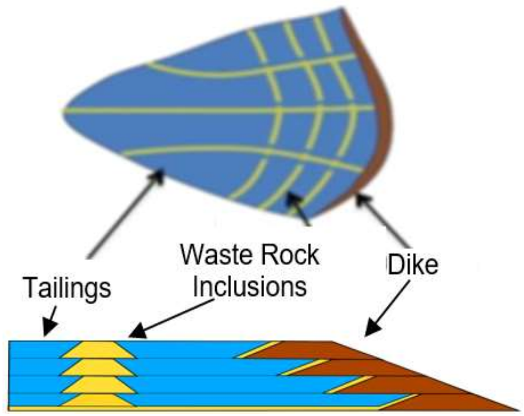

Figure 1. Schematic illustration of a tailings impoundment with WRI (modified after James and Aubertin 2010).

The use of WRI is investigated here to assess their effect on the static stability of the retaining dikes around the tailings impoundment. The article presents calculation results with safety factors obtained for impoundments during and after deposition of tailings. The results specifically demonstrate the positive effects of adding waste rock inclusions in impoundments constructed with upstream-raised dikes. These analyses are part of ongoing project aimed at providing general guidelines for the design and construction of WRI in tailings impoundments.

2 TAILINGS AND WASTE ROCK PROPERTIES

The hard rock tailings properties used for the calculations performed here were obtained from extensive laboratory and field testing campaigns conducted mainly, in recent years, at the Canadian Malartic Mine, Abitibi, QC, Canada (Poncelet 2012; L. Bolduc 2012; Contreras 2013; Golder 2014; Doucet et al. 2015; Essayad 2015; Saleh Mbemba 2016; Opris 2017; Archambault-Alwin 2017; Boudrias 2018, Grimard 2018).

The shear strength of the consolidated tailings is characterized by an effective internal friction angle ϕ' varying from 34° to 36° (and more) depending on grain size distribution, density index and effective confining stress. The effective cohesion c' is nil for these hard rock tailings. Their saturated hydraulic conductivity k_{sat} is typically between 1×10^{-5} and 1×10^{-6} cm/s, for a void ratio e between about 0.6 to 1.0.

Laboratory tests on large scale specimens of waste rock (and a few field tests) indicate that their saturated hydraulic conductivity k_{sat} is typically between 10^{-3} to 10^{-1} cm/s, depending on their density, grain size and presence of macropores (Peregoedova 2012; Martin and Aubertin 2019; Essayad 2020). The Young's modulus E of waste rock is usually between 80 and 240 MPa and the internal friction angle ϕ' varies between 37° in a relatively loose state up to 45° (and more) for denser material (Aubertin et al. 2011, 2013; Maknoon 2016).

Other tailings and waste rock characteristics are provided in the references mentioned above (see also Aubertin et al. 2019; Saleh-Mbemba et al. 2019; Jahanbakhshzadeh et al. 2019).

3 STABILITY ANALYSES OF TAILINGS IMPOUNDMENTS

The static stability of the retaining dikes depends on the stress and strength distributions within the tailings impoundment, which are directly influenced by the pore water pressures (PWP). As the impoundment is progressively filled hydraulically, the initially saturated tailings tend to consolidate under their own weight, often with a water table at or near the surface. WRI added in the impoundment are raised sequentially, with a crest above the tailings (and water) at all time.

For these analyses, the PWP and stress distributions in the tailings are calculated with the finite element code SIGMA/W. The results are then used as input for the stability analyses with SLOPE/W (Geoslope International Ltd; Krahn, 2018) to determine the critical slip surface and the minimum factor of safety, using the method of slices (Morgenstern-Price).

Figure 2 shows the conceptual model for the tailings impoundment with upstream dikes. Each dike raise is 2 m high with a crest width of 10 m and side slopes of 2.5:1 (H:V) (Figure 2a). The total height of the impoundment is 50 m at the end of construction. The base of the model is impervious, and its position is fixed in the model (no horizontal or vertical displacement). The sides of the model are also impermeable but can move vertically. The top of the model is free draining to allow dissipation of the excess PWP. Calculations have first been conducted for impoundments without the WRI (Figure 2b) and the results are then compared with those obtained below with the inclusions.

The tailings specific characteristics considered in these calculations are based on the elasto-plastic model with the Mohr Coulomb criterion, using the following properties: E = 300 kPa (Young's modulus); υ = 0.28 (Poisson's ratio); γ_{dry} = 17 kN/m3 (dry unit weight); ϕ' = 35° (effective internal friction angle), c' = 0 (effective cohesion) and $k_{sat} = 5\times10^{-5}$ cm/s.

In addition to the tailings, the numerical models contain waste rock that forms the starter dike and raised dikes, with the following properties: $k_{sat} = 5\times10^{-5}$ cm/s, ϕ' = 40°; c' = 0, n = 0.40 (porosity) and γ_{dry} = 20 kN/m^3.The waste rock in the inclusions is also homogeneous with $k_{sat} = 2\times10^{-2}$ cm/s, ϕ' = 40°, c' = 0, n = 0.4 and γ_{dry} = 19 kN/m^3 (based on Peregoedova 2012; Boudrias 2018; Essayad 2020).

The cross section of the model for the tailings impoundment shown in Figure 2b has a global external slope of 8:1 (H:V); this slope was varied for different cases. The tailings impoundment, filled to a final height of 50 m, extends to a horizontal distance of 416 m from the starter dike.

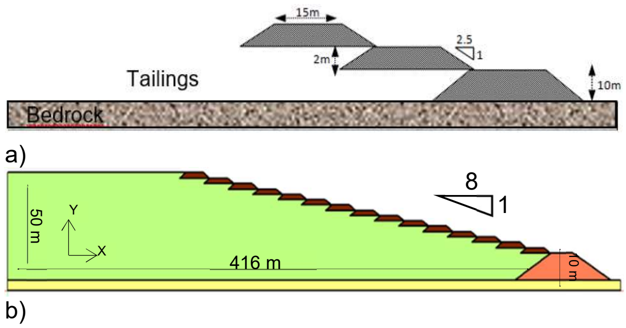

Figure 2. Cross section of the tailings impoundment with the external retaining dikes raised upstream; a) three construction steps; b) the complete model used to analyze the impoundment (without inclusion).

The work presented here follows previous investigations which showed that WRI can greatly influence water drainage and dissipation of excess PWP in tailings impoundments (e.g. Jaouhar et al. 2011, 2013; L. Bolduc and Aubertin 2014; Saleh Mbemba et al. 2019). Other simulations have also demonstrated the positive effect of WRI on the dynamic (seismic) stability of reinforced impoundments (e.g. James and Aubertin, 2012; Ferdosi et al. 2015; Jahanbakhshzadeh et al. 2019). The new calculations presented here have been conducted to assess for the first time the impact of adding WRI in tailings impoundments on static stability.

Figure 3 shows the critical slip surface with the lowest FS obtained with SLOPE/W using the Morgenstern-Price method for the tailings impoundment shown in Figure 2b, with a 8:1(H:V) slope. The FS of 3.71 (Fig. 3a) was evaluated after 26 years, with a deposition in 9 layers, when all the excess PWP were dissipated. Figure 3b shows that adding one WRI (with a width W = 25 m) near the central part of the upstream dikes increase the value of FS to 4.22 for the same slip surface. The most critical slip surface, which is located downstream of the inclusion in this case, is associated to a value of FS = 4.18 (Figure 3c). The slip surface for the impoundment with two inclusions (W = 25 m and center-to-center spacing S = 225 m) shown in Figure 3d (same as in Fig. 3a), corresponds to a minimum FS of 4.42; the minimum FS for the critical surface with two WRI is similar to the one obtained for Fig. 3c. The are thus some clear benefits from adding one or two inclusions on the stability of this tailings impoundment.

Figure 4 shows the stability calculation results immediately after the disposition of the final tailings (9th) layer (thickness of 6 m) at t = 22 years. This sudden addition of this layer of tailings (saturated slurry) generates excess PWP. The loose tailings recently added is given a lower strength with ϕ' = 30° in the short term. Under these idealized (and simplified) conditions, the critical slip surface (Figure 4a) for the unreinforced impoundment is located near the crest of the upper raises of the tailings dikes, with a corresponding factor of safety FS of 1.48. Figure 4b shows the short-term critical slip surface of the impoundment for the same deposition conditions, but with two WRI (W = 25 m, S = 140 m). The minimum FS is 2.65 in this case (only the highest inclusion is involved in the FS calculation for this critical surface). These results confirm that adding WRI near critical location(s) enhance the static stability of the retaining dikes.

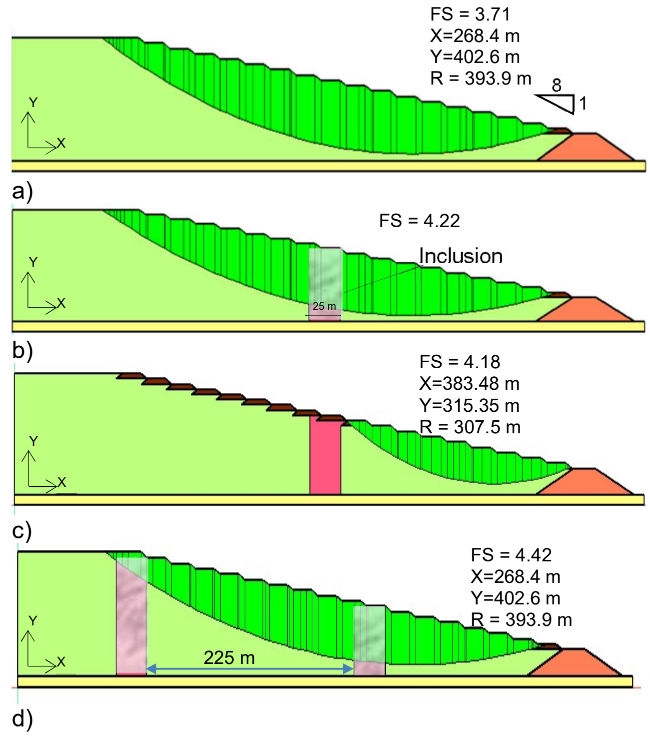

Figure 3. Critical slip surfaces, position of the centers of rotation (X, Y, R), and FS values obtained with SLOPE/W using the Morgenstern-Price (MP) method (and stress-based calculation) for the impoundment after 26 years a) no inclusion; b) with one inclusion and the same slip surface as in (a); c) critical slip surface with one inclusion; d) with two inclusions for the same slip surface as in (a).

Additional calculations have been conducted to assess the impact of other factors on the impoundment static stability, including the spacing between the WRI. In some cases, such as for the impoundment shown in Fig. 4b, only one of the WRI interacts with the critical slip surface so the spacing between the WRI doesn't affect the value of FS in such instances. There are other cases however for which S can become a key factor for static stability (and even more for dynamic stability; e.g. Ferdosi et al. 2015; Jahanbakhshzadeh et al. 2019).

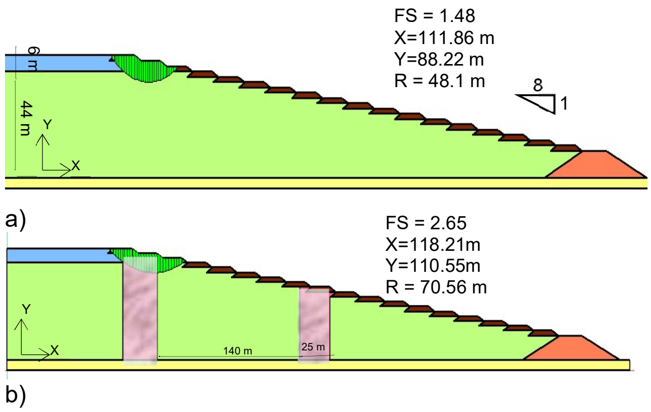

Figure 4. Critical slip surfaces, centers of rotation (X, Y, R), and values of FS immediately after the top tailings layer disposition (9th layer) at *t* = 22 years, a) unreinforced impoundment; b) with two inclusions.

Another factor investigated here relates to the influence of natural segregation (and grain size separation) of the tailings particles, which often happens after hydraulic deposition of the tailings slurry from the dike crest in the impoundment. The coarse (sandy) particles then tend to settle near the point of discharge while the finer particles move further away in the pond along the gentle surface slope (e.g. Vick 1990; Aubertin et al. 2002b; Blight 2010). This aspect has been introduced in the stability analyses using the conceptual model shown in Figure 5a. In these calculations, a zone of sandy (coarser grained) tailings is located near (and below) the dikes raided upstream. This zone of sandy tailings extends to a distance of about 34 m from the dikes. The sandy tailings have a higher hydraulic conductivity, $k_{sat} = 2\times10^{-3}$ cm/s, and a larger internal friction angle $\phi' = 37°$ (compared with 35° for the finer tailings) Figure 5 shows the critical slip surfaces for the impoundment with segregated tailings under equilibrium stresses and PWP.

Results in Figure 5b can be compared with Figure 3a for unreinforced impoundments (no WRI). The calculations indicate that the FS value is increased slightly, from 3.71 to 3.8, when the effect of segregated tailings is included in the manner presented here. Figure 5c further shows that adding a WRI increases more markedly the value of FS, to 4.42, for the same slip surface (as in Fig. 5b). The FS value is even larger, at 4.82, with two inclusions for the same slip surface, as shown in Figure 5d. Figure 5e shows that the critical slip surface is located downstream of the WRI in this case, with FS = 4.20.

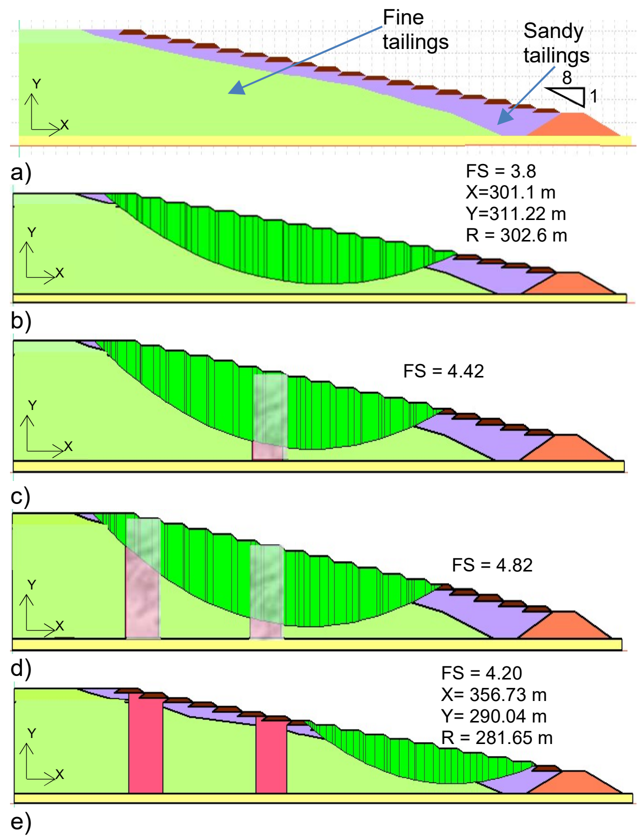

Figure 5. Geometry, critical slip surfaces, centers of rotation (X,Y, R), and values of FS for the impoundment with a zone of sandy tailings (near the dikes) under equilibrium PWP after 26 years a) conceptual model without inclusion; b) model without WRI; c) with one inclusion for the same slip surface as in (a); d) with two inclusions with the same slip surface as in (a); and e) critical slip surface with two inclusions.

Figure 6 presents the critical slip surface and the corresponding FS for the same geometry as in (Fig. 5a, for a calculation performed at *t* = 22 years, just after hydraulic disposition of the final layer (6 m thick, with $\phi' = 30°$ for the slurry). The results in this figure can be compared with those in Figure 5. The critical slip surface under such very short-term condition is located near the crest of the dikes (Figure 6a) and goes through the sandy tailings zone, leading to a factor of safety FS =1.70. Figure 6b shows that the minimum FS is increased to 2.96 for the tailings impoundment with two WRI (*S* = 100 m) including one located within the same critical surface. The most critical slip surface for this impoundment is shown in Figure 6c, with FS = 2.80 (only one WRI plays a role here).

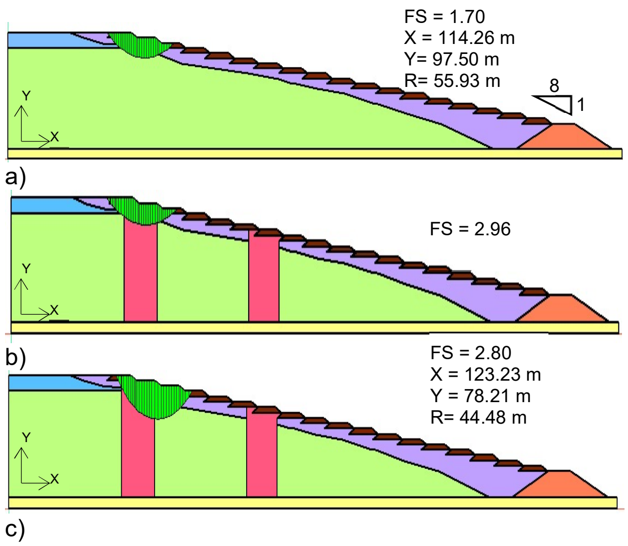

Figure 6. Critical slip surfaces, centers of rotation (X, Y, Z), and the values of FS obtained at t = 22 years, immediately after the top tailings layer disposition (9th layer), a) no inclusion; b) with two inclusions with the same slip surface as in (a); and c) critical slip surface with two inclusions.

Figure 7a shows the conceptual model for a tailings impoundment with upstream dikes constructed with a slope of 3:1(H:V). The critical slip surface, with a minimum FS of 1.95, is shown in Figure 7b (for equilibrium PWP). Figure 7c shows that adding two WRI increases the value of FS to 2.03 for the critical slip surface.

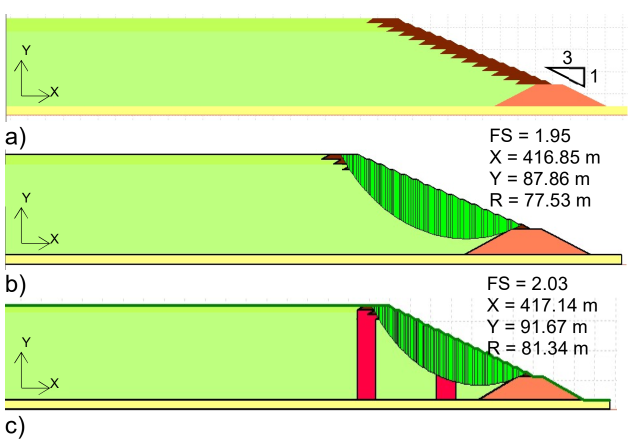

Figure 7. Geometry, critical slip surfaces, centers of rotation (X, Y, R), and values of FS obtained for the impoundment with a slope of 3:1 (H:V) at equilibrium after 26 years a) conceptual model without inclusion; b) with the corresponding critical slip surface and c) with two inclusions.

Figure 8 finally presents the critical slip surface for the same model as in Figure 7a, at t = 22 years, immediately after the disposition of the final tailings (9th) layer (6m thickness and ϕ' = 30°). Under such short-term condition, the excess PWP reduces the factor of safety to 1.2 for a critical slip surface located near the crest of the dikes, as seen in Figure 8a. Figure 8b indicates that adding two WRI (W = 13 m, S = 50 m) at selected locations increases the minimum value of FS to 1.88 (for the critical slip surface) .

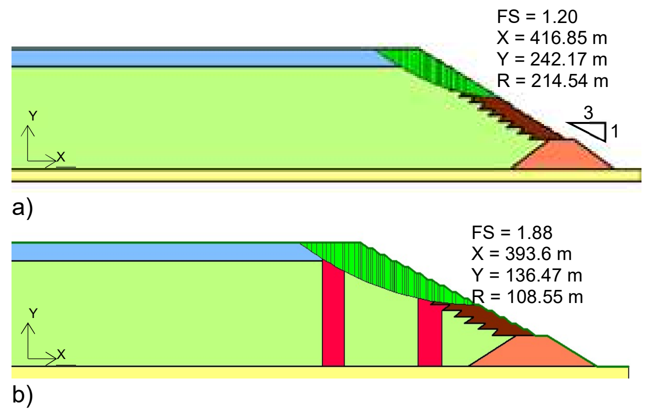

Figure 8. Critical slip surfaces, centers of rotation (X, Y, R), and values of FS) at t = 22 years immediately after the top tailings layer disposition (9th layer, a) without WRI and b) with two inclusions.

4 CONCLUSION

Static stability calculations have been conducted with Sigma/W and Slope/W (Geoslope International Ltd 2018) to assess the response of tailings impoundments as a function of the deposition conditions, upstream dikes slope, presence of waste rock inclusions, and other factors.

The results demonstrate that WRI can be integrated in an impoundment to improve static stability. The effect of WRI is considered for equilibrium PWP and for conditions when the excess PWP generated after deposition of the final tailing layer reduce the effective stress and strength. The results illustrate how the use of WRI can be used to increase a critical FS. The results shown here illustrate how the addition of WRI can help improve the static stability of upstream raised dikes around tailings impoundment for different situations. The simulations indicate, among other aspects, that the increase in the value of FS is generally more significant in the short term, when stability is often more critical.

Other factors, not considered here, can also influence the stability of tailings in an impoundment including the hydraulic conductivity of the saturated tailings, their thickness and compressibility and the deposition sequence. These are being investigated as part of the ongoing work to better understand their effects and optimize the design of WRI.

The results presented here can provide preliminary guidelines to consider the static response of tailings impoundment with WRI. Additional simulations conducted with dynamic (seismic) loading have also demonstrate that WRI can have a major impact on tailings impoundment stability (Ferdosi et al. 2015; Aubertin et al. 2019; Jahanbakhshzadeh et al. 2019; Zafarani et al. 2020), The available results demonstrate that this construction method has the potential to significantly reduce the risks associated with tailings disposal in surface facilities.

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