Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-122

Recent developments on the use of waste rock inclusions to improve the static and seismic stability of tailings dams

Michel Aubertin[1], Abtin Jahanbakhshzadeh[1,2], Samuel Yniesta[1]
[1] Polytechnique Montréal, QC, Canada, [2] AtkinsRéalis, Montréal, QC, Canada

ABSTRACT: The analysis and design of retaining dams for tailings impoundments raise significant geotechnical challenges to address the risk of instability during and after construction and upon seismic loading. Large scale applications have shown that waste rock inclusions (WRI) added within the impoundment can improve its stability by accelerating tailings drainage and consolidation, and by providing structural reinforcement. This paper gives an overview of the WRI technique and summarizes recent results from stability analyses conducted to assess their effect on the static and seismic stability of tailings impoundments with progressively raised upstream dams (dikes). The (quasi-) static analyses are based on effective stress calculations that consider the generation and dissipation of excess porewater pressures induced by sequential deposition of tailings layers. The dynamic analyses performed to evaluate the behavior of retaining dams during earthquakes illustrate how WRI can be used to improve the seismic response of tailings impoundments. Additional remarks are also provided on other aspects related to the use of WRI and the role they play with tailings management.

KEYWORDS: Tailings dams; Waste rock inclusions; Reinforcement; Drainage; Transient conditions; Slope stability; Seismic loading.

1 INTRODUCTION

The geotechnical stability of tailings disposal facilities remains a significant challenge for the mining industry around the world, as demonstrated by the numerous failures that have occurred in recent years (e.g. Morgenstern et al., 2016; Roche et al., 2017; Robertson et al., 2019; Santamarina et al., 2019; Franks et al., 2021; Zabolotni et al., 2022; EOS, 2025). The breach of a retaining dam (or dike) often leads to uncontrolled tailings flow, with major impacts on local communities and ecosystems. Various approaches based on integrated mine wastes management can be considered to address geotechnical hazards and minimize the risks (Aubertin, 2023). These include the use of reliable construction methods for the impoundment, such as opting for central-axis or downstream dikes made with appropriately selected, high strength materials on competent foundations. The addition of strategically placed waste rock inclusions (WRI) in the impoundment can also be very helpful to improve stability by providing enhanced drainage, accelerating tailings consolidation and adding structural reinforcement (Aubertin et al., 2002, 2011; James and Aubertin, 2009; James et al., 2013). Extensive investigations have been conducted over the last two decades to evaluate how WRI can best be used to improve the geotechnical and environmental performance of tailings impoundments, during the mining operation and upon closure for site reclamation (Aubertin et al., 2021).

The WRI technique involves the use of coarse-grained mine waste rock, having a much higher strength and larger hydraulic conductivity than fine-grained tailings, to create rows that provide a shorter pathway for horizontal drainage to accelerate tailings consolidation in the impoundment while providing reinforcement. WRI act somewhat similarly to gravel columns used in soft soil deposits. Such inclusions are raised sequentially during tailings deposition and impoundment construction. The continuous rows of waste rock located along selected routes within the impoundment are constructed progressively as tailings are deposited hydraulically over many years. A layer of waste rock can also be placed at the base of the pond near and on the sides of the external dikes to further accelerate drainage and consolidation. The set of WRI divide the impoundment into (partly) interconnected cells, and can significantly reduce the size of the waste rock piles on the mine site. Figure 1 shows a photo of one of the waste rock inclusions, with a crest width between 12 to 25 m, constructed at the Canadian Malartic mine located west of Val-d'Or (Québec, Canada); the figure also includes a schematic representation of WRI in a tailings impoundment

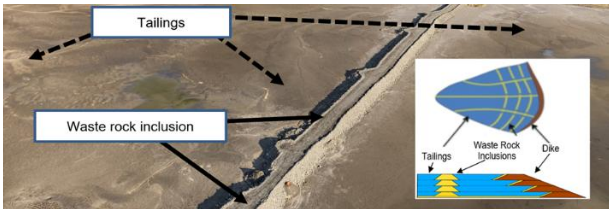

Figure 1 Aerial view of a portion of the tailings impoundment at the Canadian Malartic mine showing one of the 25m-wide waste rock inclusions; a schematic of WRI in an impoundment is also shown (adapted from James et al., 2013, 2017, and Aubertin et al., 2021).

This paper recalls the basic features of the WRI technique and summarizes some of the recent work performed to investigate their effects on the stability of tailings impoundment constructed with upstream dams (dikes), considering the evolving effective stress state during progressive tailings deposition and seismic loading. Additional aspects are also briefly discussed in the latter part of the paper, with more information and results provided in the cited references.

2 MAIN CHARACTERISTICS OF WRI

The initial investigation on waste rock inclusions, which started about 25 years ago, was largely conceptual. It then quickly became more focussed on specific geotechnical and operational issues when the WRI technique was applied on a large scale for the first time at the Canadian Malartic (formerly Osisko) mine, which is one of the largest gold producers in Canada. The main objectives of the work done in collaboration with this mine, located west of Val-d'Or (Québec, Canada), was to evaluate the interactions between WRI and the adjacent tailings in terms of drainage and consolidation, and assess the geotechnical behavior and stability of the impoundment under static and dynamic (earthquake) loadings. The extensive experimental work performed since then includes a detailed characterization of the hydro-geotechnical properties of the tailings and waste rock produced at the mine operation (James et al., 2017;

Essayad, 2021; Jahanbakhshzadeh and Aubertin, 2022). This was complemented by field instrumentation and monitoring, and specialized laboratory testing and physical modelling (Pépin et al., 2012; Opris, 2017; Boudrias, 2018; Essayad, 2021; Saleh-Mbemba and Aubertin, 2019, 2021a,b). The experimental results have been used to calibrate and validate (in part) various types of constitutive models and numerical simulations (see below).

The main results from these studies have largely confirmed the initial assumptions about the beneficial effects of WRI on the overall tailings disposal site performance. These also led to guidelines and recommendations for WRI design and construction, considering their effects on the hydro-geotechnical response of impoundments for different geometries and loading conditions (Aubertin et al., 2021).

Additional studies are still being conducted to further assess the effect of WRI, with the most recent ones focusing on the geotechnical stability of tailings impoundments with upstream dikes raised sequentially with progressive filling during the mining operation (Jahanbakhshzadeh and Aubertin, 2023, 2024). The effect of seismic loading, which is now part of the systematic design process, is also being investigated further with numerical dynamic analyses (Aubertin, 2024). This paper summarizes some of the main results obtained from the most recent investigations; more details are included in the references.

3 EFFECTIVE STRESS ANALYSES UNDER TRANSIENT CONDITIONS

Stability analysis of the retaining dams confining the tailings in the impoundment is sometimes performed with steady-state stress calculations, but this approach is deemed unrealistic (and unsafe) in many instances, given the effect of tailings hydraulic deposition and its impact on the factor of safety FS (see below). Alternatively, the analysis can be made with a total stress approach for undrained conditions, using a $\phi = 0^\circ$ type analysis. Application of the latter approach however raises questions (and concerns) about the evaluation and applicability of the undrained shear strength S_u in the case of tailings from hard rock mines, as these may often show a frictional strength component under most testing conditions (unlike most soft clays). It can be recalled that a realistic evaluation of the S_u (kPa) value for relatively loose, contracting (normally consolidated) tailings, should lead to a normalized strength ratio S_u/σ'_v (where σ'_v is the effective overburden stress, kPa) close to 0.22 (e.g. Vick, 1990; Aubertin et al., 2011, 2021; Reid et al., 2022; Jahanbakhshzadeh and Aubertin, 2022). But when this value is used to evaluate FS with the limit equilibrium method (LEM), the results often lead to critical results, particularly for upstream dikes with a relatively steep slope (Jahanbakhshzadeh and Aubertin, 2024). The direct measurement of S_u can be challenging and uncertain for low plasticity tailings, in part because the undrained behavior assumption may not reflect their actual response during in-situ tests. It is thus deemed preferable to use a coupled analysis that considers the transient evolution of the porewater pressures (PWP) and effective stresses to assess the stability of conventional and reinforced tailings impoundments.

A transient stability analysis can take into account the fact that the geotechnical response of an impoundment depends on the evolving total and effective stress state and the related tailings shear strength. These are influenced by the PWP that varies during the hydraulic filling of the impoundment with the tailings produced at the mill. The sequential deposition of initially loose (slurry) tailings layers, with a typical pulp density P (or solid content) between 30 and 45% - or higher with a densifying process (e.g. Martin et al., 2006), tends to increase the total stress and induce excess PWP. After the addition of each new layer, the fine-grained tailings consolidate under their own weight as the excess PWP dissipate in the saturated tailings (Aubertin et al. 2021).

Effective stress analyses can be conducted to evaluate the tailings response and impoundment stability at different times, based on properties measured under well-controlled conditions. Coupled analyses can then consider the evolution of the PWP and effective stresses and related shear strength under transient conditions, before an equilibrium is reached (if ever). The coupled stress-strain distribution obtained (typically) from finite element simulations then serves to calculate the factor of safety FS with the limit equilibrium method (LEM) or with a strength reduction factor (SRF) approach (Jahanbakhshzadeh and Aubertin, 2021, 2023, 2024).

This type of stability calculations has been performed with the commercially available codes Sigma/W and Slope/W (GeoStudio, 2019). The calculation results summarized here were used to assess the response of tailings impoundments with upstream dikes for different heights and slope angles and to compare cases with and without WRI. These analyses consider the effect of each tailings layer added on the impoundment surface, which generates excess PWP (due to their total weight) and reduce the effective stress, shear strength and corresponding factor of safety. Although such transient conditions are deemed more representative of the actual conditions for an active tailings impoundment, they are not commonly applied to stability analysis in practice.

The results obtained with this approach, such as those shown below, indicate that short-term conditions after each new layer deposition, analyzed in terms of the effective stresses, are often the most critical for the impoundment stability as they correspond to the lowest value of FS (before increasing over time). Comparative calculations also demonstrate that the short-term value of FS is larger and its rise is more rapid in the presence of well positioned WRI, thus improving the overall tailings impoundment stability. As mentioned above, the contribution of WRI, which create a horizontal drainage pathway that accelerates tailings consolidation and provide reinforcement, is somewhat analogous to gravel columns in soft soil deposits. WRI are however continuous and much larger (typically 12 to 25 m at the crest) than vertical drains, and these are constructed progressively during tailings hydraulically deposition on both sides. The contribution of the WRI to tailings consolidation and water drainage (L. Bolduc and Aubertin, 2014; Saleh-Mbemba et al., 2019; Saleh-Mbemba and Aubertin, 2021a, b, c) thus accelerates the PWP dissipation and increases the effective stresses.

The impact of adding WRI in an impoundment is illustrated here with the results of an effective stress analysis under transient conditions for the model shown in Figure 2. This conceptual model of the impoundment with upstream dikes includes two WRI (width W = 25 m, edge-to-edge distance S = 140 m), located under the top dike and at mid-height. The response of a similar conventional impoundment (without the inclusions) is also analysed. The calculations were conducted with Sigma/W for the evolving effective stress state, and then with Slope/W to calculate the factor of safety using the Morgenstern-Price LEM approach. The calculation results presented below correspond to the period following the addition of the top tailings layer in the impoundment that is filled with ten 4-m-thick layers added every two years (based on a 2-m dike/layer added each year) (Jahanbakhshzadeh and Aubertin, 2021). The addition of the last layer of saturated tailings on the surface generates excess PWP and reduces the effective stresses. The calculated factor of safety FS, shown in Figure 3, is initially lower than 1.5 in this case, which is below commonly applied design criteria for tailings impoundment (Aubertin et al., 2002, 2011; Jahanbakhshzadeh and Aubertin, 2024). With the two WRI, the short-term value of FS increases above 3.0 for the critical slip surface, demonstrating that these WRI significantly improve the initial stability of the impoundment. Over time, the excess PWP (shown at a depth of 41.5 m and a distance of 328 m from the starting dike), generated by adding the top layer (and each new layer below), tends to dissipate so there is an increase in FS for both cases; the FS value then becomes almost the same when an equilibrium is reached.

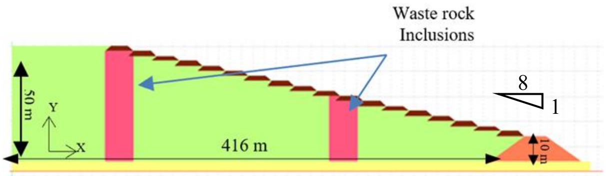

Figure 2. Conceptual model of the tailings impoundment with upstream dikes and two WRI; the model also includes the stiff foundation and starter dike (adapted from Jahanbakhshzadeh and Aubertin, 2021).

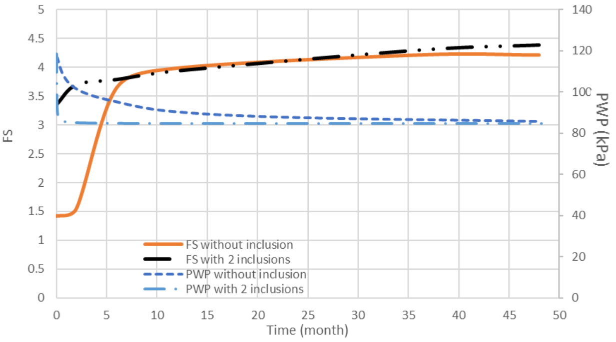

Figure 3. Calculation results showing the evolution of the factor of safety FS and PWP (at a depth of 41.5 m) obtained from a coupled analysis with the LEM after the addition of the top tailings layer in an impoundment with an external slope of 8H:1V (modified from Jahanbakhshzadeh and Aubertin, 2021).

These calculation results (and others) indicate that the impact of the WRI on slope stability is more pronounced shortly after the deposition of new tailings layers. This effect can be even larger when the analysis considers that the very loose tailings recently added have a lower shear strength (Jahanbakhshzadeh and Aubertin, 2024); detailed analyses also show how WRI affect the location of the critical slip.

Results such as those shown above illustrate the benefits of adding WRI for the static stability of tailings impoundments during the mine site operation, when hydraulic deposition occurs.

Additional calculations have been conducted to assess the impact of other factors on the impoundment static stability, including the external slope angle and spacing between the WRI (Jahanbakhshzadeh and Aubertin, 2021, 2024). Complementary results (not shown here) indicate that in many cases (similar to Figure 2), only one of the two inclusions interacts directly with the critical slip surface that tends to develop near the top surface. There are nonetheless cases for which the WRI position is an influential factor, depending on the dikes raising sequence and the external slope angle. The geometric characteristic of the WRI is also relevant to optimize their drainage contribution and for dynamic stability analyses, as will be discussed in the following.

4 DYNAMIC ANALYSES UNDER SEISMIC LOADING

The seismic behavior of tailings impoundments is important for earthquake prone areas, as is the case in some parts of Canada, particularly in the provinces of British-Columbia and Québec. The seismic response is best analyzed using dynamic numerical analyses, which are now frequently mandated for the design process (Aubertin, 2024).

The dynamic response of conventional and reinforced impoundments was evaluated for a variety of geometries and loading conditions, based on simulated excess porewater pressure, cyclic stress ratio, and induced displacement. The finite-volume software FLAC (Version 8; Itasca, 2016) was used for these numerical simulations. The initial series of analyses (e.g. James et al., 2012; Ferdosi et al., 2015a,b; Aubertin et al., 2019; Jahanbakhshzadeh et al., 2019) were performed with the UBCSand constitutive model (Beaty and Byrne, 2011) to represent the cyclic response of hard rock tailings; the most recent simulations (including the results shown below) were conducted with the PM4Sand model (Boulanger and Ziotopoulou, 2017) to simulate the tailings cyclic behavior (Zafarani et al., 2020, 2025; Zafarani, 2022; Contreras et al., 2023a,b).

The dynamic analyses all followed a similar modeling procedure to simulate the seismic response of tailings impoundments built with the upstream dikes (central-axis dikes were also considered in a few cases). This procedure first consists in simulating the static conditions to define the initial state of stresses, strains and porewater pressures, under hydro-geotechnical equilibrium using the Mohr-Coulomb elasto-plastic model. The results from the static phase served as initial conditions, upon which the UBCSand or PM4Sand model was applied for the dynamic analysis under seismic loadings; more details on the various steps for these analyses are provided elsewhere (Zafarani, 2022; Contreras, 2022; Aubertin, 2024).

Many simulations were performed to analyse tailings impoundments with different heights and slopes, WRI configurations, and seismic loads to assess the influence of each parameter on the dynamic response. Figure 2, shown above, represents the basic geometry of the impoundment model with different material zones, including a bedrock foundation layer to transmit seismic loading. The starter dike, typically 10 m-high, and subsequent 2 m dike raises are made of waste rock in contact with the saturated tailings. Tailings migration into WRI is not considered in the simulations (see discussion below). The impoundment model extends far enough from the top dike (> 100 m) so it doesn't affect the analysis.

The reference mesh size was defined based on the highest frequency wavelength input. The typical element size of 1 m by 1 m can transmit ground motions frequencies up to 20 Hz through the model. The latter frequency is deemed sufficient for seismic events from relatively stable continental regions (such as Québec, Eastern Canada) characterized by higher frequency events compared to other more active seismic regions (Atkinson, 1996; Zafarani, 2022).

The boundary conditions applied to the model for the static calculation consist of a fixed horizontal position on both sides, no vertical displacement at the base and a zero-value of the PWP at the tailings and dikes surface. Placing the phreatic surface at the top of the impoundment represents a worst-case scenario for dynamic stability, and is representative of the water level for many active tailings impoundments with ongoing hydraulic slurry deposition. The elastoplastic Mohr-Coulomb constitutive model was used in the static stage to simulate the behavior of all materials in the impoundment, using properties obtained from laboratory and field investigations.

The dynamic analyses were conducted with a free field boundary on both sides of the impoundment model. The selected ground motions (horizontal accelerations) applied at the base were obtained from various documented sources and selected to represent various seismic loading scenarios. The fluid boundary conditions were the same as for the static phase. For the results shown here, the PM4Sand model parameters were evaluated from cyclic tests results on tailings (Contreras et al., 2023b).

The simulations input considered here were based on the Loma Prieta (California, USA) 1989 earthquake, with a magnitude M_w of 6.93. The selected recordings show an average frequency of 6.5 Hz, a *PGA* of 0.3 g, an Arias Intensity of 1.2 m/s, and a duration D_{5-95} of 13.72 s (PEER, 2019). Several other ground motions were applied in additional simulations, but the tendencies reported here reflect the main trends obtained for different cases with and without WRI (Zafarani, 2022; Contreras, 2022).

The seismic response of the impoundment was evaluated based on the evolution of the stress state and displacements. Results are presented here in terms of the normalized horizontal displacement of the downstream slope, SAR_x, which is a dimensionless variable quantifying the relative deformation along the external face of the upstream dike (Zafarani et al., 2020; Zafarani, 2022). The value of SAR_x is calculated from the horizontal displacement at each nodal point on the downstream slope surface at the end of shaking, divided by its initial elevation above the bedrock. The normalized horizontal displacement SAR_x was computed for different cases to evaluate the effect of various factors on the behavior of the impoundment. The SAR_x values presented below, adapted from Zafarani et al. (2020), are expressed as a function of the non-dimensional geometric parameter W_{vs} defined by the WRI volume and spacing between the starting dike and inclusions (Zafarani, 2022),. Figure 4 shows representative results that illustrate how the SAR_x value changes with W_{vs} for three different heights of the impoundment (30 m, 40 m, and 50 m), with a downstream slope of 8H:1V. It is seen that the SAR_x values obtained for the model with a height 30 m are relatively constant, thus reflecting the small horizontal displacements in this case. Increasing the height of the model to 40 and 50 m however leads to much larger displacements SAR_x for lower W_{vs} values (i.e. smaller or fewer WRI).

Other simulations conducted for different downstream slopes, from 7H:1V to12H:1V (not shown here), show the influence of this important geometric factor, with the steeper slopes leading to larger SAR_x. The results also demonstrate how strategically placed WRI in the impoundment can decrease the displacements, with a more pronounced effect for the steeper slopes; in all cases, larger WRI (or larger W_{vs}) lead to smaller SAR_x (Zafarani et al., 2020; Zafarani, 2022). The simulated variations of SAR_x also indicate that the tailings height (thickness) has a more significant impact on the seismic response when compared with the downstream slope angle, for the range of values considered.

Further analyses with different seismic Intensity Measures, *IM*, indicate that the value of SAR_x is best correlated with the Peak Ground Velocity, *PGV*, and Velocity Spectrum Intensity, *VSI* (Zafarani et al., 2025) An optimum correlation is obtained by combining one of these two velocity *IM* with the commonly used *PGA* (Zafarani, 2022; Zafarani et al., 2025).

Additional simulations indicate that the WRI in an impoundment may help reduce the relative volume of liquefied tailings and greatly diminish the displacements (up to a factor of 10, and more) during an earthquake (Contreras et al., 2023a). These analyses were also used to assess the post-seismic response of tailings impoundments, which can become unstable beyond the seismic loading period (Contreras et al., 20223a). The effect of WRI on impoundments stability was also evaluated based on time-dependant displacements and velocities during the shaking and post-shaking phases. A stable post-seismic behavior is then characterized by a rapid decrease (over a few seconds) of the velocities, down to zero, following the end of the earthquake. As expected, conventional (unreinforced) impoundments with a steeper slope are more likely to fail during or after the earthquake than reinforced impoundments. It was also shown that reinforcement of the impoundment with WRI can greatly reduce the displacements and velocities of the tailing during the seismic and post-seismic phases, resulting in an increased stability compared to the conventional impoundment (Contreras, 2022).

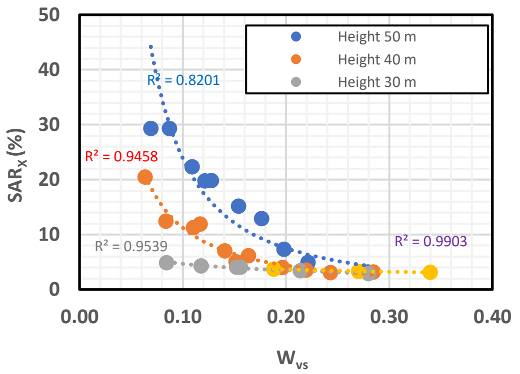

Figure 4. Normalized horizontal displacement (SAR_x) along the external slope of the impoundment as a function of the WRI volume and spacing parameter (W_{vs}) for reinforced impoundments with a downstream slope of8H:1V and heights of 30, 40 and 50 m (adapted from Zafarani et al., 2020)

Results from various simulations show how WRI can be used to enhance the seismic stability of tailings impoundments. In critical cases, reinforcement could allow the impoundment to withstand significant ground motions without a breach, even when tailings become liquefied (Ferdosi et al., 2015a,b; Contreras et al., 2023a).

Other aspects of the seismic behavior of tailings, including methods to evaluate their liquefaction potential (James and Aubertin, 2016), were also investigated, but are not addressed here; these must nonetheless be considered for the seismic analysis and design of impoundments (Aubertin, 2024).

5 COMPLEMENTARY ASPECTS

As already mentioned, WRI can also have a major impact on tailings consolidation and drainage inside the impoundment (Aubertin et al., 2021). This aspect has been investigated through experimental testing, physical and numerical modelling and field observations (L. Bolduc and Aubertin, 2014; Boudrias, 2018; Saleh-Mbemba et al., 2019; Saleh-Mbemba and Aubertin, 2019, 2021a, b, c). This has led to the development of a simplified analytical solution to assess the flow rate at the interface and the amount of water transferred from the tailings to a WRI, considering saturated and unsaturated flow under transient and (quasi) steady-state conditions. This solution (not presented here) is based on a modified Dupuit-Forchheimer equation for steady-state, which gives the maximum flow rate during the deposition cycle, followed by a progressively decreasing rate. The solution also includes tailings consolidation due to both horizontal and vertical drainage, evaluated based on Terzaghi's solution.

WRI have also been shown to locally increase the density of the tailings at their vicinity due to the accelerated consolidation and drainage. Although this has not been commonly done in previous work, this effect could be included in the analysis for both static and seismic stability of reinforced impoundments. Additional analyses were however conducted to assess the stability of impoundments when some of the tailings desaturate due to a lowering of the water table, especially close to a WRI (Jahanbakhshzadeh and Aubertin, 2025). In this instance, the negative PWP (suction) may induce desiccation and densification of the unsaturated tailings, which can then acquire a higher stiffness and shear strength due to their lower void ratio and to the suction induced apparent cohesion (Narvaez et al., 2015; Essayad and Aubertin, 2020; Aubertin, 2025). The positive impact of creating unsaturated conditions in the tailings on impoundment stability was recently demonstrated with coupled analyses involving unsaturated water flow, evolution of the PWP and slope stability calculations with the contribution of an apparent cohesion in the tailings (Jahanbakhshzadeh and Aubertin, 2025).

Migration of tailings with water drainage into the waste rock during placement is another important aspect that has also been investigated using laboratory physical modelling and field observations at the Canadian Malartic mine. These have shown that some tailings movement may occur across the interface with the waste rock, but this process doesn't affect much the drainage capacity of the WRI, as the local hydraulic conductivity remains much larger (by 2-3 orders of magnitude) than that of the adjacent tailings. Recommendations were also formulated to minimize the impact of this potentially detrimental process (Essayad, 2021; Aubertin et al., 2021).

Other factors can also be considered in stability analysis, including the effect of depth (and consolidation) on the tailings porosity, strength and hydraulic conductivity. Variability of tailings properties due to a change in grain size, initial water (solid) content, segregation and layering can also be deemed relevant for site-specific conditions.

This article focuses on tailings impoundments constructed with upstream dikes, which are still commonly used in the mining industry (mainly for financial reasons), despite the many reservations expressed by various groups over the years (e.g. Aubertin et al., 2002, 2011; Aubertin, 2023). It is emphasized again here that other options should also be considered to construct the retaining dikes, improve impoundment stability, and reduce the risks. The potential benefits have been demonstrated for instance by analysing the response of central-axis raised dikes built with strong materials such as compacted waste rock (Jahanbakhshzadeh et al., 2019). These results and others have clearly demonstrated that stronger raised dikes can lead to much more stable conditions when compared with upstream dikes.

The design of WRI must also consider additional aspects not discussed here, such as their construction sequence, material transport scheduling and costs. Planning for WRI should also consider that these give more flexibility for tailings management and site reclamation (Aubertin et al., 2011, 2021; James et al., 2013, 2017; Aubertin, 2023). It is finally recalled that the overall design process for tailings impoundment must also look into many other factors, including the impact of large (extreme) precipitations, which are becoming more frequent and unpredictable as a results of climate change.

6 CONCLUSION

This article summarizes the work conducted in recent years to assess the benefits and limitations related to the use of waste rock inclusions (WRI), which aim at accelerating tailings consolidation and drainage while providing reinforcement to improve the static, seismic and post-seismic stability of tailings impoundments. Guidelines for optimizing the position and size of WRI in an impoundment were also developed, based on practical considerations and key technical aspects. The paper focuses more specifically on the effect of WRI on the stability of upstream dikes during sequential filling and on the seismic stability of the impoundment, based on representative calculation results; more detailed results are presented in the references.

Other benefits may also come from the use of WRI, such as the possibility of initiating site closure earlier (with a cover for instance) and facilitating tailings deposition and management by compartmentalizing the impoundment. WRI can also be used to submerge potentially acid generating waste rock under water in the impoundment, thus preventing their oxidation, while reducing the volume of waste rock in piles. Mining companies, consulting firms and governmental agencies are thus encouraged to consider the WRI technique as an alternative to conventional deposition.

7 ACKNOWLEDGEMENTS

The authors acknowledge the financial support from NSERC, the contributions from the partners of the Research Institute on Mines and the Environment (RIME) at Polytechnique Montréal, and the collaboration from colleagues and graduate students (see list of references).

8 REFERENCES

Atkinson, G. M. (1996). The high-frequency shape of the source spectrum for earthquakes in eastern and western Canada. *Bull. Seismological Society of America*, *86*(1A): 106-112.

Aubertin. M., Mbonimpa. M., Jolette, D., Bussière, B., Chapuis, R.P., James, M., and Riffon, O. 2002. Stabilité géotechnique des ouvrages de retenue pour les résidus miniers: Problèmes persistants et méthodes de contrôle. *Proc. Symp. Environnement et les mines*, Rouyn-Noranda, QC, CIM. CD-ROM, pp. 526-552.

Aubertin, M., Bussière, B., James, M., Jaouhar, E.M., Martin, V., Pépin, N., Mbonimpa, M., and Chapuis, R.P. 2011. Vers une mise à jour des critères de stabilité géotechnique pour la conception des ouvrages de retenue de résidus miniers. *Proc. Symp. Mines et Environnement*, Rouyn-Noranda, QC. CIM, 38p.

Aubertin, M., Jahanbakhshzadeh, A., and Yniesta, S. 2019. The effect of waste rock inclusions on the seismic stability of a tailings impoundment. *Proc. 7th Int. Conf. Earthquake Geotechnical Engineering*, Rome, Italy, pp. 1220-1227.

Aubertin, M., Jahanbakhshzadeh, A., Saleh Mbemba, F., Yniesta, S., and Pednault C. 2021. General guidelines for the design and construction of waste rock inclusions in tailings impoundment. *Proc. GeoNiagara 2021*, CGS, 8p.

Aubertin, M., 2023. Pour une gestion environnementale responsable des rejets miniers. Mémoire, Consultation. *Développement harmonieux de l'activité minière.* MRNF QC, 19 p.

Aubertin, M., 2024 Analyse dynamique de la stabilité des ouvrages miniers : Revue des méthodes et outils disponibles et orientations générales. *Technical Report, MELCCFP*. Québec, 38 p.

Aubertin, M., 2025. Unsaturated properties of mining wastes: From experimental measurements to large scale applications. *Proc. PanAm Unsat 2025 Conference*, Ottawa, ISSMGE, 20p.

Beaty, M.H. and Byrne, P.M., 2011. UBCSAND constitutive model Version 904aR. Document report: UBCSAND Constitutive Model on Itasca UDM Web site: http://www.itascaudm.com/pages/continuum.html

Boudrias, R., 2018. Évaluation numérique et expérimentale du drainage et de la consolidation de résidus miniers à proximité d'une inclusion de roches stériles. *Master Thesis*, Polytechnique Montréal, QC, Canada

Boulanger, R. W., and Ziotopoulou, K., 2017. PM4Sand (Version 3): A sand plasticity model for earthquake engineering applications. Center for Geotechnical Modeling Report No. UCD/CGM-15/01, University of California, Davis, Calif.

Contreras, C. A., 2022. Détermination de la stabilité sismique et post-sismique des parcs à résidus de roche dure avec et sans inclusions de roche stérile pour des aléas faibles, intermédiaires et élevés des régions minières de l'est du Canada. h. D. Thesis, Polytechnique Montréal.

Contreras, C., Yniesta, S. and Aubertin, M. 2023a. Improvement of tailings impoundment seismic and post-seismic stability using densification and waste rock inclusions. *Can. Geotech. J.,* 60(11): 1629-1644.

Contreras, C. A., Yniesta, S., Jahanbakhshzadeh, A., and Aubertin, M. 2023b. Calibration of the PM4Sand model for hard-rock mine tailings based on laboratory and field testing results. *Can. Geotech. J.* 60(7): 966-977.

EOS 2025. The Landslide Blog by Dave Petley - https://eos.org/landslide-blog

Essayad, K. 2021. Évaluation multi-échelle de l'instabilité interne et de la migration des résidus à travers les inclusions de roches stériles. Ph.D. Thesis, Polytechnique Montréal.

Essayad, K., Pabst, T., Aubertin, M. and Chapuis, R.P. 2018. An experimental study of the movement of tailings through waste rock inclusions. *Proc. GeoEdmonton 2018*, CGS, 8p.

Essayad, K., and Aubertin, M., 2020. Consolidation of hard rock tailings under positive and negative pore-water pressures: testing procedures and experimental results. *Can. Geotech. J.* 58(1): 49-65,

Ferdosi, B., James, M., and Aubertin, M. 2015a. Effect of waste rock inclusions on the seismic stability of an upstream raised tailings impoundment: a numerical investigation. Can, Geotech. J., 52(12): 1930-1944.

Ferdosi, B., James, M., and Aubertin, M. 2015b. Numerical simulations of seismic and post-seismic behavior of tailings. Can. Geotech. J. 53(1): 85-92.

Franks, D.M., Stringer, M., Torres-Cruz, L.A. et al. 2021. Tailings facility disclosures reveal stability risks. *Sci Rep 11*, 5353.

GEO-Studio, 2019. Stress-deformation modeling with SIGMA/W 2019 and Slope stability with Slope/W. (GeoSlope).

Itasca Consulting Group, Inc. (Itasca). 2016. FLAC – Fast Lagrangian Analysis of Continua. Version 8.00. Minneapolis.

Jahanbakhshzadeh, A., Aubertin, M., Yniesta, S., and Zafarani, A. 2019. On the seismic response of tailings dikes constructed with the upstream and center line methods. Geosciences for Sustainability, *Proc. GeoSt-John's 2019*, CGS 7 p.

Jahanbakhshzadeh, A., Aubertin, M. 2021. Effect of the configuration of waste rock inclusions on the static stability of tailings impoundments. Geosciences for Sustainability, *Proc. GeoNiagara 2021*, CGS 7p.

Jahanbakhshzadeh, A., and Aubertin, M. 2022. Main results from an extensive geotechnical characterization of hard rock tailings from an open pit gold mine. Geosciences for Sustainability, *Proc.GeoCalgary 2022*, CGS. 8p..

Jahanbakhshzadeh, A., and Aubertin, M. 2023. Influence factors affecting the static stability of tailings impoundments with waste rock inclusions. Geosciences for Sustainability, *Proc. GeoSaskatoon 2023,* CGS. 8p.

Jahanbakhshzadeh, A., and Aubertin, M. 2024 Effective Stress Analyses to Assess the Stability of Progressively Raised Upstream Dikes for Tailings Impoundments with Waste Rock Inclusions, *Geotech Geol Eng*., 42:3193‑3212.

Jahanbakhshzadeh, A., and Aubertin, M. 2025. Impact of Unsaturated Conditions on the Stability of Tailings Impoundments with Waste Rock Inclusions. *Proc. GeoManitroba 2025*. CGS. 10p.

James, M. and Aubertin, M. 2009. The use of waste rock inclusions in tailings impoundments to improve geotechnical and environmental performance. *Proc. Tailings and Mine Waste 2009*, Banff, Alta. pp. 233–245.

James, M., and Aubertin, M. 2012. The use of waste rock inclusions to improve the seismic stability of tailings impoundments. *Proc. GeoCongress 2012,* Geo-Institute, ASCE, pp. 4166-4175.

James, M., Aubertin, M., and Bussière, B. 2013. On the use of waste rock inclusions to improve the performance of tailings impoundments. *Proc. 18th Int. Conf. Soil Mechanics and Geotechnical Engineering,* ISSMGE, Paris, France, pp. 735-738.

James, M., Aubertin, M., Bussière, B., Pednault, C., Pépin, N., and Limoges, M. 2017. A research project on the use of waste rock inclusions to improve the performance of tailings impoundments. *Proc. GeoOttawa 2017*, CGS,. 8p.

James, M. and Aubertin, M., 2016. Comparison of numerical and analytical liquefaction analyses of tailings. *J. Geotechnical and Geological Engineering.* (2017) 35: 277–291 (online, Oct. 2016).

L. Bolduc, F. and Aubertin, M. 2014. A numerical investigation of the influence of waste rock inclusions on tailings consolidation, *Can. Geotech. J.* , 51(9): 1021-1032.

Martin, V., Aubertin, M. and McMullen, J. 2006. Surface disposal of paste tailings. *Proc. 5th ICEG Environmental Geotechnics: Opportunities, Challenges and Responsibilities for Environmental Geotechnics,* Cardiff, UK, pp. 1471-1478.

Morgenstern N, Vick S, Viotti C, and Watts B. 2016. Report on the immediate causes of the failure of the Fundao Dam. Fundao Tailings Dam Review Panel, 76 p.

Narvaez B, Aubertin M, and Saleh-Mbemba F. 2015. Determination of the tensile strength of unsaturated tailings using bending tests. *Can. Geotech. J.* 52:1874–1885.

Opris, RI. 2017. Caractérisation de résidus miniers à l'aide d'essais de pénétration au cône. Master Thesis Polytechnique Montréal, QC, Canada.

PEER (Pacific Earthquake Engineering Research Center), 2019. Earthquake and station details. https://ngawest2.berkeley.edu/ (Consulted on September 2019. see Zafarani, 2022)

Pépin, N., Aubertin, M., and James, M. 2012. Seismic table investigation of the effect of inclusions on the cyclic behaviour of tailings. *Can. Geotech. J.* 49(4): 416–426.

Reid D., Fanni R., and DiDonna P. 2022 The effect of tamping conditions on undrained shear strengths of a non-plastic sandy silt tailings. *Can Geotech J* 59(6):783‑795

Roche, C., Thygesen, K., and Baker, E. (Eds.). 2017. Mine Tailings Storage: Safety Is No Accident, A UNEP Rapid Response Assessment. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal.

Robertson, P.K., de Melo, L., Williams, D.J., and Wilson, G.W. 2019. Report of the expert panel on the technical causes of the failure of Feijão Dam. [http://www.b1technicalinvestigation.com/].

Saleh-Mbemba, F. and Aubertin, M. 2019. Physical modeling of tailings consolidation near a waste rock inclusion. *Proc. GeoSt.John's 2019*, CGS, 8p.

Saleh-Mbemba, F., Aubertin, M. and Boudrias, G. 2019. Drainage and consolidation of mine tailings near waste rock inclusions. *Proc. 87th Annual Meeting of the International Commission of Large Dams - ICOLD-CIGB 2019*, Ottawa, 2: 3296-3305.

Saleh-Mbemba, F. and Aubertin, M. 2021a. Physical model testing and analysis of hard rock tailings consolidation considering the effect of a drainage inclusion. *Geotech. Geol. Engng J.*, 39: 2777-2798.

Saleh-Mbemba, F. & Aubertin, M. 2021b. Physical and numerical modelling of drainage and consolidation of tailings near a vertical waste rock inclusion. *Can. Geotech. J*., 58(9):1263-1276.

Saleh-Mbemba, F. and Aubertin, M. 2021c. Analysis of the water flow transferred from tailings to waste rock inclusions. *Proc. GeoNiagara2021,* CGS, 8p.

Santamarina, J.C., Torres-Cruz, L.A., Bachus, R.C. 2019. Why coal ash and tailings dam disasters occur. *Science* 364 (6440), 526-528..

Stark, T.D., Moya, L., and Lin. L., 2022 Rates and Causes of Tailings Dam Failures. *Advances in Civil Engineering*, ID 7895880, 21p.

Vick, S.G. 1990 Planning, Design and Analysis of Tailings Dams. BiTech Publishers.

Zabolotni, E. Morgenstern, N.R. and Wilson, G.W. 2022. Mechanism of failure of the Mount Polley Tailings Storage Facility. *Can. Geotech. J.* 59: 1503–1518.

Zafarani, A. 2022. Development of a Seismic Design Procedure of Tailings Impoundments Reinforced with Waste Rock Inclusions. *Ph.D. Thesis*. Polytechnique Montreal

Zafarani, A., Yniesta, S. and Aubertin, M. 2020. Effect of height and downstream slope on the seismic behavior of tailings impoundments reinforced with waste rock inclusions. *Proc. GEOVirtual 2020,* CGS, 8p.

Zafarani, A., Yniesta, S., Aubertin, M., Nguyen, V., Quinn, J. 2025. Comparative Assessment of Seismic Intensity Measures for Different Tailings Types. *Proc. Tailings and Mine Waste 2025*. Banff, AB, 12p.