The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
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The effect of waste rock inclusions on the seismic stability of a tailings impoundment

M. Aubertin, A. Jahanbakhshzadeh & S. Yniesta
RIME, Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, QC, Canada

ABSTRACT: Surface disposal of tailings from hard rock mines raises various geotechnical issues, including the risk of seismic instability. Waste rock inclusions (WRI) may be used to improve the geotechnical response of tailings impoundments. The advantages of WRI include accelerated consolidation and drainage of the tailings and physical reinforcement of the impoundment. A major research project is underway in Québec, Canada, to assess the geotechnical response of tailings impoundments with WRI. The research program includes extensive laboratory characterisation, physical model tests, in-situ monitoring at a mine site where WRI are in use, and a series of numerical simulations to evaluate the response of retaining dikes under various loading conditions. Results from the latter component of this project are presented here, with a summary of the related geotechnical investigation. The numerical modelling calculations simulating the behavior of dikes during earthquakes illustrate how WRI can be used to enhance the seismic response of a tailings impoundment.

1 INTRODUCTION

The geotechnical behavior of mine tailings impoundments has received increased attention in recent years following major dike failures. One of the most critical issues regarding geotechnical stability relates to the seismic response of the impoundment, which may be significantly influenced by the behavior of tailings made of low plasticity silty materials in a loose state (for hard rock mines). The tailings can exert significant loads on the retaining dikes during an earthquake, particularly when these tailings undergo strength loss (up to liquefaction) due to the generation of excess porewater pressures. Examples of seismically-induced tailings impoundment failure include the Cerro Negro tailings dikes (Chile) in 1985 (Castro & Troncoso 1989) and the 1994 Tapo Canyon Tailings Dam failure following the Northridge earthquake in California (Harder & Stewart 1996). The 2010 Maule earthquake, which occurred during a dry period in Chile, also affected the stability of a few tailings dikes (Verdugo & González 2015).

Innovative tailings impoundment design approaches are needed to address these concerns. Investigations performed in recent years have indicated that waste rock inclusions (WRI) can be used to improve the stability of tailings impoundments by providing reinforcement and drainage (Aubertin et al. 2002; James & Aubertin 2010). This co-disposal technique mainly consists of placing rows of waste rock within the impoundment prior to each stage of hydraulic filling with tailings. A layer of waste rock can also be placed along the bottom and on the sides of the impoundment to further accelerate drainage and consolidation, but this option is not considered here. The continuous rows of waste rock that create the WRI are positioned along selected routes to divide the impoundment into (partly) interconnected cells (James et al. 2013). A tailings impoundment with waste rock inclusions is shown schematically in Figure 1, with a photo of the Canadian Malartic mine site where WRI are being constructed.

The WRI technique is, in some ways, similar to gravel columns used to accelerate drainage in soft soil deposits and to provide reinforcement, with the difference that inclusions are placed during filling, in tandem with the tailings in the impoundment.

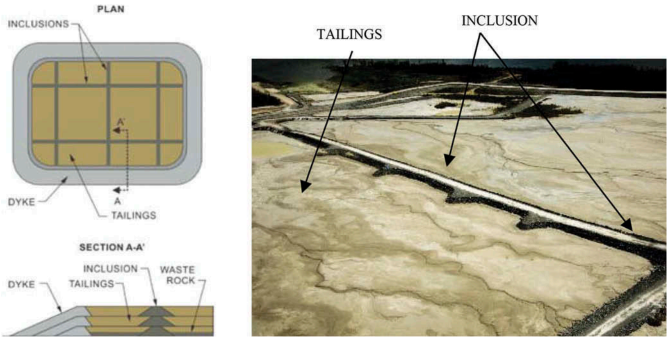

Figure 1. a) Schematic representation of a tailings impoundment with waste rock inclusions (James et al. 2017); b) one of the waste rock inclusions in the tailings impoundment at the Canadian Malartic mine (Québec, Canada).

The use of waste rock inclusions in tailings impoundments has been studied for over 15 years using conventional and specialized laboratory testing, physical models and numerical simulations. Results from generic and conceptual investigations have indicated that WRI strategically positioned in a tailings impoundment may induce a number of beneficial effects on its environmental and geotechnical performance (James et al. 2013, 2017). These include an increased rate of excess pore water pressures dissipation during the hydraulic (slurry) deposition of tailings (L. Bolduc & Aubertin 2014; Saleh Mbemba 2016), improved static and dynamic stability of the impoundment (Ferdosi et al. 2015), and reduced displacements of the tailings and dikes during and following an earthquake (James 2009; Ferdosi 2015). WRI can also accelerate post-shaking dissipation of excess pore water pressures generated within the tailings and help prevent destabilization of the downstream slope of the retention dikes following an earthquake.

The encouraging results from these early studies have led to a major research program conducted in collaboration with industrial partners. It aims at better quantifying the effects of inclusions in tailings impoundments and to develop guidelines for their general use. A large part of this project is taking place at the tailings disposal site of the Canadian Malartic Mine (west of Val-d'Or, Québec, Canada), which is constructed with WRI (see Figure 1b). The research project includes field instrumentation and monitoring, conventional and specialized laboratory testing, physical modelling and numerical simulations (James et al. 2017). It also aims at evaluating the interactions between WRI and the adjacent tailings with respect to tailings intrusion into the waste rock, short and long-term drainage capacity of the inclusions, stress transfer from the tailings to the WRI, and the behavior of the retaining dikes under static and dynamic (earthquake) loadings.

This paper summarizes some of the results obtained so far, and addresses more specifically the seismic stability of the tailings impoundment by presenting simulated responses to earthquake loading, with and without inclusions.

2 SITE CHARACTERISTICS AND MATERIALS PROPERTIES

The daily production at the Canadian Malartic hard rock gold mine is about 55,000 tons of ore and 125,000 tons of waste rock. The tailings produced from ore processing at the mill are transported as a slurry to the large impoundment, covering over 470 hectares (with a maximum height of about 40 m when completed), and deposited with a pulp density (solids content) near 65%. The crest of the WRI has a minimum width of 15 m, and these are raised by up to 3 m, 2 to 3 times a year. The tailings are deposited from the crest of the external dykes (raised upstream) and WRI.

Extensive characterization work has been performed to assess the hydro-geotechnical behavior of these tailings. Tests on tailings were conducted using oedometers, large size instrumented columns and triaxial cells. Additional tests have also been performed in Tempe cells and pressure plates, to assess the water retention curve of the tailings, their shrinkage characteristics and related unsaturated behavior. The detailed results, taken from different sources, are summarized in L. Bolduc & Aubertin (2014), Saleh Mbemba (2016), and Grimard (2018). The low plasticity tailings, which contain more than 80% of fine (mostly silty) particles (< 75 μm), have a saturated hydraulic conductivity k_{sat} between $1{\times}10^{-8}$ and $1{\times}10^{-7}$ m/s, depending of the void ratio e (with e between 0.6 and 1.0 approximately). The compression index C_c is about 0.09 and the coefficient of volume change m_v is around 0.17 MPa^{-1}. The normally consolidated tailings have an effective angle of internal friction ϕ' between 36° and 38°, for confining stresses below 600 kPa. The tailings have no effective cohesion ($c' = 0$), and the critical state is reached at a ratio $p'/q \sim 0.6$.

The cyclic behavior, including the potential for dynamic liquefaction, was also studied using cyclic triaxial tests and an innovative triaxial-simple shear device (in collaboration with Université de Sherbrooke; Archambault-Alwin 2017). The experimental results indicate that the shear strain and excess pore water development follow the same trends as for relatively clean sand. For instance, the Cyclic Resistance Ratio (CRR) can be expressed using the well-known relationship with the number of cycles N leading to liquefaction (or N_{LIQ}) developed for sand (e.g. Idriss & Boulanger 2008; James et al. 2011):

$$CRR = A_0 N^{-b} \tag{1}$$

For the Canadian Malartic mine tailings, the experimental value of A_0 varies from 0.22 to 0.34 (with most data ≤ 0.25) and exponent b is between 0.16 to 0.29 (typically ≥ 0.23), depending on the grain size, porosity, type of loading and confining stress (Archambault-Alwin 2017).

The characteristics of coarse waste rock from hard rock mines are also being evaluated using laboratory tests on relatively large-scale samples and a few field tests. Available results indicate that the saturated hydraulic conductivity is between 10^{-3} to 10^{-1} cm/s, depending on their density, grain size distribution and presence of macropores. Young's modulus is in the range between 80 and 240 MPa and the internal friction angle varies from about 37° in a relatively loose state up to 45° (and more) for dense waste rock (Aubertin et al. 2011, 2013).

The geotechnical parameters obtained from this experimental investigation are used for numerical simulations of various conceptual cases inspired by the Canadian Malartic mine impoundment; they have been considered for the simulations presented below.

In addition to the characterization work on the material properties described above, the interaction between waste rock forming the inclusions and the adjacent tailings is also investigated. For instance, drainage and consolidation of tailings in contact with waste rock was assessed with physical models (Saleh Mbemba 2016). Migration of tailings into the waste rock is also studied in the laboratory and in the field, as this phenomenon could reduce the drainage capacity of inclusions (Essayad et al. 2018). Results available to date indicate that the migration of fine particles in the WRI does not significantly influence water drainage.

Complementary field work has also been done, with some measurements still underway. The field work comprises cone penetration testing (CPT) and measurements in eight boreholes drilled near a WRI (through specially constructed platforms). Tailings were sampled and instruments were installed to measure pore water pressures, volumetric water content, and displacements (James et al. 2017). The monitoring data are used to evaluate the actual behavior of the tailings near the inclusion and to compare the observed and predicted (simulated) behaviors.

3 DYNAMIC NUMERICAL ANALYSES

A series of numerical simulations are conducted to assess the response of the tailings in an impoundment having characteristics inspired by those at the Canadian Malartic mine site. The simulations represent various scenarios that include many cases that differ from the actual conditions at this site. Some simulation results are compared with in-situ data (and laboratory physical modelling) for validation and calibration purposes (mostly regarding consolidation and drainage – not shown here), while others are used to evaluate alternative configurations, considering the life cycle of the mine and (future) evolution of material properties following deposition, consolidation, and drainage, as a function of the height and location of the WRI.

The response of the tailings impoundment is also simulated for various earthquake loadings, considering different WRI configurations (which differ from the WRI at the mine site in most cases). The numerical analyses include static and dynamic loadings. Post-shaking analyses are also conducted when failure doesn't occur during the dynamic analysis, but these results are not presented here (see also James 2009 and Ferdosi 2015). The static analyses provide the stresses and porewater pressures under equilibrium conditions, prior to earthquake shaking. The dynamic analyses involve the application of ground motions to the models to simulate the occurrence of earthquake loadings of known intensities.

The numerical analysis results shown here were obtained with version 8 of FLAC (Fast Lagrangian Analysis of Continua, Itasca Consulting Group, Minneapolis, Minnesota, USA), which is a well-known two-dimensional finite volume (finite difference) software program (earlier versions were also used for previous analyses). The large-strain mode, in plane strain, was used due to the potential for significant displacements.

The dynamic response of the impoundment is evaluated using different indicators including the calculated (simulated) cyclic stress ratio (CSR), effective stresses and porewater pressures, and displacement characteristics (magnitude and rate based on nodal velocities).

The simulated tailings impoundment analyzed here is an upstream-raised structure consisting of a 10 m-high starter dike and up to 15 raises, 2-m-high, resulting in a total height of 40 m. The starter dike and raises are made of waste rock. The crest width of the raised dikes is 15 m. The side slopes are 2.5:1 (H:V) for the starter dike and each raise. Tailings were placed in the impoundment up to the crest; the top tailings surface is flat, and the water table is at the surface. The representative (partial) geometry of the impoundment is presented on Figure 2; larger views are shown below (see Figures 3 and 5).

Subsurface conditions below the impoundment consist of a 2-m-thick layer of dense glacial till underlain by hard, moderately fractured bedrock.

Typical grids are constructed with over 10 000 elements. The overall length and height of the models are 497 m and 44 m, respectively (Figures 3 and 5). A "virtual" buttress composed of glacial till (which does not actually exist in the field) is placed on the upstream end of the model for stability reasons and to provide a representative far field boundary (James 2009; Ferdosi 2015). The resulting width of the impounded tailings area is 218 m, measured from the crest of the starter dike to the toe of the buttress. The maximum height of the impoundment, H, is 40 m.

Two constitutive models are used for material behavior: the well-known Mohr-Coulomb elasto-plastic model for the foundation, dikes and WRI, and the UBCSAND model (Park & Byrne 2003;Beaty & Byrne 2011; see also Ferdosi et al. 2015) for the tailings (other dynamic simulations use different constitutive models, but these are not presented here). The UBCSAND model was developed to simulate the static and dynamic behavior of sandy soils. This model has also been shown to represent well the dynamic response of tailings from hard rock mines, in terms of porewater pressure, strain development, liquefaction and post-liquefaction behavior (James 2009; Ferdosi 2015). The material properties used by the UBCSAND model include: the corrected (clean-sand) standard penetration test blow count, $(N_1)_{60\text{-}cs}$,; constant volume friction angle, ψ'_{cv}; dry density, ρ_{dry}; saturated hydraulic conductivity, k_{sat}; and porosity, n. Parameters $(N_1)_{60\text{-}CS}$ and ψ'_{cv} are also used to determine other properties required by the model.

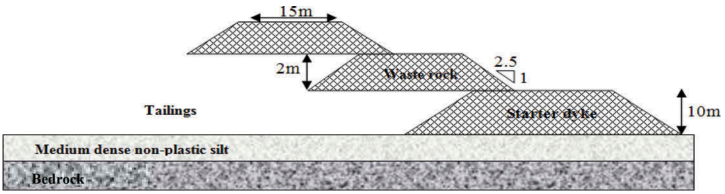

Figure 2. Cross section of the external dike made of waste rock, after three construction steps

The Mohr-Coulomb elasto-plastic formulation includes a failure (yield) envelope with a tension cutoff. The shear flow rule is non-associated and the tension flow rule is associated (Itasca 2015).

For the static analyses, the boundary conditions applied to the model consist of fixed mechanical boundaries and porewater pressures, with hydrostatic pressures within the model. For the dynamic phase, the fixed mechanical boundary conditions are removed, while the porewater pressure and flow boundary conditions are retained. A free field condition is used to apply horizontal accelerations to the base of the model and to compensate for the dynamic reactions on the ends of the model (to simulate an infinite extent).

The basic modeling assumptions and material properties can be summarized as follows:

- The tailings are normally consolidated, and their properties were obtained from in-situ and laboratory tests (see above and below).
- The waste rock forming the starter dike, raises and inclusions is characterized by a dry unit weight γ_{dry} = 20 kN/m^3, a friction angle ϕ' = 38° and a porosity n = 0.25.
- The bedrock consists of hard, moderately fractured andesite and its properties are based on published values for similar rock (James 2009; Ferdosi 2015; Itasca 2015).
- The basic properties of the relatively dense silt above the bedrock are: γ_{dry} = 16.20 kN/m^3, ϕ' = 32° and n = 0.4.
- The shear G and bulk K moduli (kPa) of the waste rock (for the inclusions and dikes) are given by the relationships developed by James (2009):

$$G = 55000(0.6 \times \sigma'_v)^{0.5} \tag{2}$$

$$K = 2.3833 \times G \tag{3}$$

where σ'_v is the effective vertical stress (kPa).

The value of $(N_1)_{60\text{-}cs}$ for the tailings was estimated from in-situ cone penetration testing and numerical simulations of cyclic direct simple shear (CDSS) testing of normally consolidated tailings (James 2009; Ferdosi 2015). The average $(N_1)_{60\text{-}cs}$ and ρ_{dry} values are 11 blows/30 cm and 1700 kg/m^3, respectively.

The sigmoidal hysteretic damping model Sig3 (Itasca 2015) was used to model both dynamic damping and shear modulus reduction with shear strain for the Mohr-Coulomb materials. Hysteretic damping in the tailings is explicitly included within the UBCSAND model, but the model is unable to produce hysteretic damping at small strains. A stiffness proportional Rayleigh damping scheme is used to introduce the latter, with a target damping ratio of 0.2% at a frequency of 15 Hz (Cundall 2006).

The seismic response of the tailings impoundment was simulated under a range of earthquake intensities, with seismic events having a moment magnitude of 6.5 to 7.5, with an assumed horizontal distance from the fault rupture of 10 to 30 km (James 2009; Ferdosi 2015).

The recently obtained simulation results presented here are for an earthquake with the following characteristics: magnitude M_w = 7; peak ground acceleration PGA = 0.378 g; Arias intensities I_x = 2.05 m/s; epicentral distance of 20 km; duration of 35 seconds. These ground motion characteristics are based on the 1988 Saguenay (Quebec) earthquake and on relationships summarized by Kramer (1996; see also James 2009 and Ferdosi 2015). The imposed seismic loading conditions are however more severe than would be expected at the mine site, to illustrate more clearly the potential effect of WRI. In general, the simulated ground motions applied to the numerical models are intended to represent specific levels of earthquake intensity, but not specific events.

Various characteristics calculated during the dynamic (and post-shaking) analyses were recorded during the 10^6 timesteps, equivalent to increments of approximately 35×10^{-6} seconds for the dynamic phase.

Figure 3 shows a cross section of the modeled tailings impoundment without WRI. Figure 4 presents the deformed geometry with the horizontal displacements of the impoundment without inclusion at the end of shaking. This figure shows that the crest of the impoundment

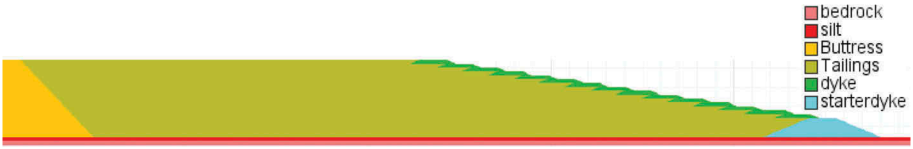

Figure 3. Model of the tailings impoundment used for the numerical simulations, L= 497 m and H = 44 m; the starter dike is 10 m high.

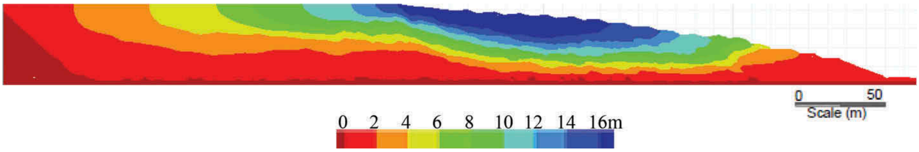

Figure 4. Final deformed geometry with horizontal displacements contours (after 35 seconds)

moved approximately 16 m in the downstream direction; such large deformations could lead to failure of the impoundment.

In the case of the impoundment without inclusion submitted to these severe loading conditions, the CSR values developed beyond the 5th second of shaking were approximately nil, indicating that there were no significant shear stresses developed when a plateau (pseudo-steady state) is reached. The retained tailings liquefied, with r_u values approaching 1, within 8 seconds (results not shown here).

The seismic response of the modified tailings impoundment with waste rock inclusions (WRI) was simulated for the same loading conditions (i.e. M_w=7), for various cases. The model with WRI considered here includes rows of waste rock placed parallel to the external, upstream dike. The vertical inclusions are 14 m wide and spaced 42 m apart (center to center) starting 14 m upstream of the starter dike, as illustrated in Figure 5 (width W = 14 m and center-to-center spacing S = 42 m).

The vertical lines labeled P1 to P5 shown on Figure 5 represent locations where key parameters have been monitored during the simulations, (i.e. horizontal displacements and accelerations (and corresponding strains), cyclic stress ratio *CSR*, vertical and horizontal stresses, excess pore-water pressures and its ratio r_u,; there are also recorded in the bedrock and top of the dikes.

The horizontal displacement of the external dyke and impoundment at the end of shaking varied locally, from 0 to 1 m, as shown in Figure 6; these are much smaller than for the unreinforced impoundment (Figure 4). This indicates that the WRI can enhance significantly the seismic response of the impoundment, by decreasing the horizontal displacements (by a factor of more than 10 in this case). Other simulations show the same tendencies, but with various contributions of the WRI depending on their configuration.

The simulations also show that the vertical effective stresses within the retained tailings and the uppermost portions of the waste rock inclusions were significantly lower than those prior to shaking due to the development of excess porewater pressures. The vertical effective stresses within the tailings are usually larger near the waste rock inclusions, indicating that their presence reduced locally the development of excess porewater pressures. The simulation also

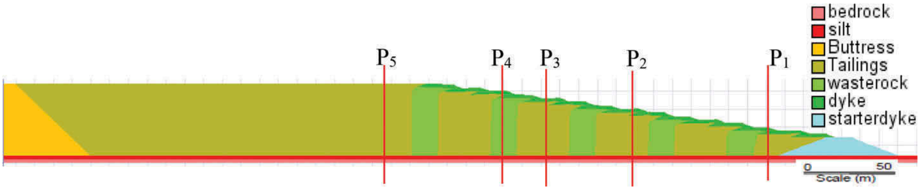

Figure 5. Model of the impoundment with WRI (with W = 14 m and S= 42 m).

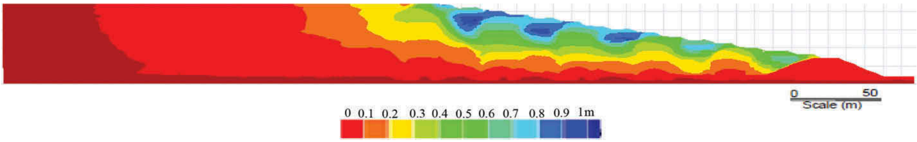

Figure 6. Final deformed geometry and horizontal displacement contour at end of shaking in the reinforced tailings impoundment (with WRI).

indicates that the pore water pressure ratio (r_u) between WRI increased at the onset of shaking and reached maximum values up to 0.8 (and more) within the first 5 to 7 seconds.

This simulation and others tend to indicate that the WRI do not reduce significantly the generation of excess pore water pressures in the tailings (except in the immediate vicinity of the inclusions). The WRI rather serve to prevent the deformation and flow due to liquefaction, while accelerating the dissipation of excess PWP after shaking (see Ferdosi et al. 2015).

4 DISCUSSION AND CONCLUSION

The numerical analyses conducted here demonstrate that a considerable improvement can be achieved with the seismic performance of tailings impoundments through the use of waste rock inclusions. The simulation results presented above, and many others (including some still underway), illustrate how WRI can be used to reduce the displacements of the crest of the dike as well as the magnitude and extent of deformation of the tailings in the impoundment. These reductions are due to the ability of WRI to resist the horizontal (shear) forces induced in the impoundment by an earthquake.

Another aspect, not addressed above, is the environmental advantages of using WRI when the mine waste contains reactive minerals (like pyrite and pyrrhotite). Ongoing work shows that with good planning, closure work on an impoundment with WRI can be started on the surface of the tailings before the end of operations. The use of WRI allows compartmentalization of the impoundment, in addition to accelerated consolidation of the tailings and physical reinforcement. This leads to additional flexibility for the management and closure of the impoundment. The WRI also favors containment of potentially acid generating waste rock, while reducing the volume of waste rock piles (or even eliminate the pile for underground mines).

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from NSERC, FRQNT and from the partners of the Research Institute on Mines and the Environment, (RIME UQAT-Polytechnique; http://rime-irme.ca/en), and the collaboration of the Canadian Malartic mine.

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