On the seismic response of tailings dikes constructed with the upstream and center-line methods

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ABSTRACT
Mining operations tend to generate large quantities of waste rock and tailings. The fine-grained tailings are generally disposed hydraulically in surface impoundment whose stability remains a major concern, following several retaining dike failures in recent years. Earthquakes are among the main causes of large-scale tailings dike breaches. Such retaining dikes are raised progressively, often using the upstream method; other, less risky, methods can also be used. This article presents numerical simulation results aimed at analyzing and comparing the seismic response of tailings dikes made of waste rock and built with the upstream and centerline methods. The effect of adding waste rock inclusions inside the tailings impoundment (with the upstream method) is also assessed. The results may help improve the stability of retention dikes and serve to develop an optimization strategy for the use of waste rock inclusions.

RÉSUMÉ
Les exploitations minières génèrent fréquemment de grandes quantités de roches stériles et de résidus. Les résidus miniers à grains-fins sont usuellement disposés hydrauliquement dans des parcs à résidus miniers dont la stabilité demeure une préoccupation majeure, comme l'indique la rupture de plusieurs digues au cours des dernières années. L'activité sismique est l'une des causes principales de ces ruptures à grande échelle. Les digues de retenue des résidus sont rehaussées progressivement, en utilisant souvent la méthode de construction amont; d'autres méthodes moins risquées peuvent aussi être utilisées. Cet article présente les résultats récents de simulations numériques visant à analyser et à comparer la réponse des digues de parcs à résidus faites de roches stériles et construites avec les méthodes amont et de l'axe-central. L'effet de l'ajout d'inclusions de roches stériles dans les parcs à résidus (avec la méthode amont) est également évalué. Les résultats pourraient servir à améliorer la stabilité des parcs à résidus et à développer une stratégie d'optimisation pour l'utilisation des inclusions de roches stériles.

1 INTRODUCTION

The stability of tailings impoundments still represents a major challenge for the mining industry, as demonstrated by major failures reported in recent years (Harder and Stewart 1996; Aubertin et al. 2002; Azam and Li, 2010; Roche et al. 2017; Strachan and Caldwell 2018; Santamarina et al. 2019). There are various ways to reduce the risks, starting with avoiding the most problematic practices. The addition of waste rock inclusions in tailings impoundments can also help improve the hydro-geotechnical behavior and stability of dikes (Aubertin et al. 2002, 2011; James and Aubertin 2010, 2012; L. Bolduc and Aubertin 2014). A few approaches are investigated here with regards to the seismic stability of retaining dikes built with waste rock around tailings impoundment.

More specifically, this article presents seismic simulation results obtained for tailings impoundments with dikes having two distinct configurations. The simulation for the upstream dikes case is loosely based on an actual mine site in Abitibi (Aubertin et al. 2019). The same characteristics are used to analyze the behavior of dikes constructed with the central-axis method (e.g. Vick, 1990; Aubertin et al. 2011). These two simulations aim to assess the effect of the construction method on seismic stability. Another simulation considers the effect of adding waste rock inclusions (WRI) in the impoundment constructed with upstream-raised dikes. These numerical calculations are part of the ongoing work conducted to provide guidelines for the optimum configuration and design of tailings impoundment and retaining dikes.

2 MATERIAL CHARACTERISTICS

The tailings properties used for the simulations shown here were characterized following an extensive field and laboratory testing campaign conducted 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, Grimard 2018; Boudrias 2018).

The hard rock tailings, which are classified as non-plastic silt (ML) per the USCS (Unified Soil Classification System), contain more than 80% of fine particles (< 75 µm).Their effective internal friction angle ϕ' is between 34° and 36° in a relatively loose state, and it can reach higher values in a denser state.

The saturated hydraulic conductivity k_{sat} of these tailings is typically between 1×10^{-8} and 1×10^{-7} m/s, depending on the void ratio e (between 0.6 and 1.0 approximately). Other tailings and waste rock characteristics are provided in the references mentioned above (see also Aubertin et al. 2019; Saleh-Mbemba et al. 2019).

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

3 NUMERICAL MODELING OF TAILINGS IMPOUNDMENT

Simulations that have been conducted with the code FLAC (version 8, Itasca 2016). This well-known finite difference program uses a Lagrangian calculation scheme and a mixed discretization zoning technique. It can simulate geotechnical problems with various geometries and conditions, including static and dynamic loadings. The dynamic numerical modeling was conducted in two steps. The first one is the analysis of the hydro-geotechnical response with the pore water pressures and stresses under static (equilibrium) conditions. The second step involved the addition of seismic loads with selected Arias intensities and frequency contents, applied at the base of the tailings impoundment model (e.g. Ferdosi et al. 2015a; Aubertin et al. 2019).

3.1 Tailings Impoundment with upstream dikes

Figure 1 shows the conceptual model for the tailings impoundment with the upstream dikes. The starter dike height is 10 m and each dike raise is 2 m, with a crest width of 15 m and side slopes of 2.5:1 (H:V). The total height of the impoundment is 40 m (end of construction).

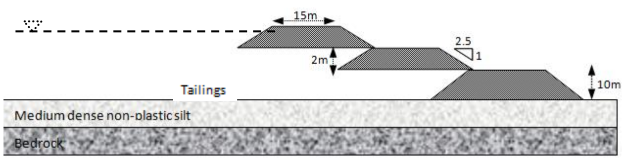

Figure 1. Cross section of the external retaining dikes after three construction steps with the upstream method.

Two constitutive material behavior models were applied for these numerical analyses. The Mohr-Coulomb elasto-plastic model was used for the dikes made of waste rock, the waste rock inclusions (when applicable), buttress and the foundation. The UBCSAND model (Beaty and Byrne 1998, 2011; Park and Byrne 2003; see also Ferdosi et al. 2015a) was used for the retained tailings and non-plastic silt layer. This model has been shown to generally provide a fairly good representation of the dynamic response of tailings from hard rock mines in terms of pore water pressure, stress-strain, liquefaction and post-liquefaction behaviors (James 2009; Ferdosi 2015).

For the first step (static loading), the boundary conditions applied to the numerical model block the horizontal displacement on both sides and the vertical displacement at the base of the model; hydrostatic (equilibrium) pore water pressures are also applied. For the second step (with dynamic loading), the fixed mechanical (displacement) boundary conditions are removed while the pore water pressure and flow boundary conditions are retained. A free field condition with horizontal accelerations is applied at the base of the model. More details are given in Ferdosi et al. (2015a) and Aubertin et al. (2019).

The waste rock in the simulated starter dike, raised dikes and WRI is considered homogeneous, with $k = 10^{-1}$ cm/s (hydraulic conductivity), $\phi' = 38°$ (internal friction angle); $n = 0.25$ (porosity) and $\gamma_{dry} = 20$ kN/m^3 (dry unit weight).

The following relationships developed by James (2009) were used for the waste rock shear G and bulk K moduli (kPa) (dikes and inclusions):

$$G = 55000(0.6 \times \sigma_v')^{0.5} \quad [1]$$

$$K = 2.3833 \times G \quad [2]$$

where σ_v' is the in-situ effective vertical stress (kPa).

An average $(N_1)_{60\text{-}cs}$ of 6 blows/30 cm was adopted in the simulations with the UBCSAND model for the tailings in the impoundment, with an average dry density ρ_{dry} of 1700 kg/m^3.

A 2 m thick layer of medium dense silt is located below the tailings; the silt properties are $\gamma_{dry} = 16.20$ kN/m^3, $\phi' = 32°$ and $n = 0.4$. The bottom layer is made of 2 m of moderately fractured rock; its properties are $\gamma_{dry} = 22$ kN/m^3, $\phi' = 40°$ and $n = 0.1$ (based on published values; e.g. Chen et al. 1996; James 2009, Ferdosi 2015; Itasca 2016).

The sigmoidal hysteretic damping model sig3 (Itasca 2016) was applied to the waste rock (dikes and inclusions) and also to the buttress (virtual) that was added to the model to control the boundary conditions (James, 2009; Ferdosi, 2015). This model considers that hysteretic damping increases and the shear modulus decreases when the shear strains progress. Rayleigh damping was also applied with a ratio of 0.2% at a frequency of 15 Hz (Cundall 2006).

Rayleigh damping was applied to the bedrock, using adjusted damping ratios for high and low frequency earthquake records (so that the acceleration at the top of the bedrock was the same as the input acceleration record). The imposed Rayleigh damping ratios for the bedrock for the high and low frequency earthquake ground motions were 3% and 2%, respectively, with a center frequency of 5 Hz (Ferdosi et al. 2015b).

Seismic events with a moment magnitude between 5.9 to 7.5, at an (assumed) horizontal distance of 10 to 30 km were considered in various simulations (James 2009; Ferdosi 2015; Aubertin et al. 2019). The earthquake ground motions (horizontal accelerations) were applied to the base of the model.

Representative simulations results are presented in the following for an earthquake magnitude $M_w = 7$, a peak ground acceleration $PGA = 0.378$ g, an Arias intensity $I_x =$

2.05 m/s, an epicentral distance of 20 km and a duration of 35 seconds (based in part on ground motion records from the 1988 Saguenay (QC) earthquake). The characteristics of the imposed seismic event are more severe than expected in the Abitibi mining area, to highlight the potential influence of the factors assessed here on a comparative basis.

Figure 2 shows the cross section of the modelled tailings impoundment with upstream-raised dikes. The tailing impoundment is filled to a final height of 39 m, 1 m below the crest of the final dike (total height H = 40 m); the horizontal distance from the starter dike to the base of the stiff (virtual) buttress is 560 m.

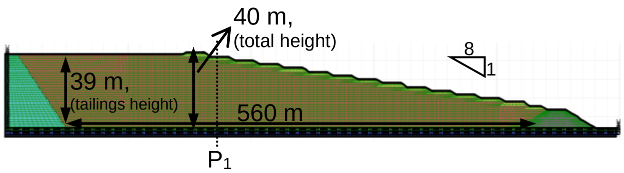

Figure 2. The 2D model used to simulate the tailings impoundment.

The interstitial pore water pressure distribution (at equilibrium) given by the static simulation is shown in Figure 3. The phreatic level is at the surface, and all the materials are saturated.

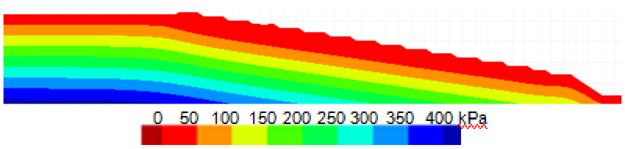

Figure 3. Pore water pressure distribution under static conditions.

Figure 4 presents results from the dynamic analysis, showing the deformed geometry with the horizontal displacements of the impoundment during shaking. This analysis stopped after 16 s, i.e. before the end of the 35 s ground motion, (due to excessive deformation (of at least one element). These results show that the crest of the impoundment was displaced by about 18 m horizontally in the downstream direction. Such large deformation would lead to a dike failure.

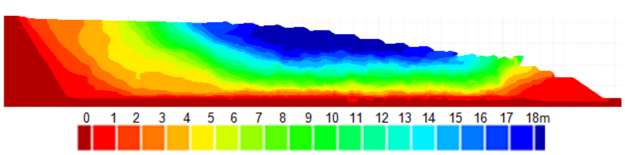

Figure 4. Iso-contours of the horizontal displacements with the final deformed geometry (after 16 s).

A FISH function (programmed in FLAC) was used to extract values of the pore water pressure ratio r_u (i.e. excess pore water pressure over the initial effective vertical stress) at different locations, including along the vertical line labeled P_1 shown in Figure 2. Figure 5 indicates that most of the retained tailings reached liquefaction, as revealed by the large increase in the value of r_u (~ 1) within a few seconds, at two different elevations (near the base and top of the tailings).

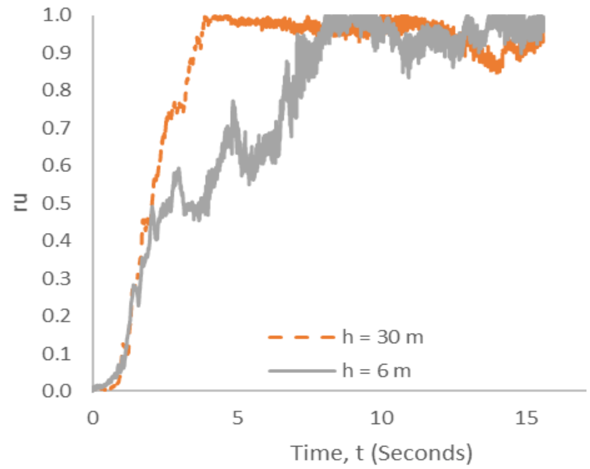

Figure 5. Pore water pressure ratio (r_u) in the tailings impoundment during the seismic event (up to 16 s) at location P_1 (see Figure 3)

The seismic loading also produced increasing cyclic stress ratio *CSR* (the ratio of uniform cyclic shear stress T_{cyc} to initial effective normal stress σ'_{v0}), up to 0.1 for the first 4 seconds of shaking followed by a significant reduction (results not shown here). The latter reduction is indicative of damping associated with the development of shear strains and high excess pore water pressures that significantly reduced the ability of the tailings to transmit subsequent horizontal accelerations.

3.2 Impoundment with centerline-raised dikes

Simulations were also conducted with FLAC to assess the dynamic behavior and stability of retaining dikes raised with the centerline method. The conceptual model of the tailings impoundment with the centerline-raised dike is shown in Figure 6. In this case, each raise is 6 m high, with a crest width of 9 m; the external slope is 5:2 (H:V) and the inside slope is 5:3 (H:V). The total height of the tailings impoundment is again 40 m. The vertical line labeled P_1 shown on Figure 6 represents one of the locations where key parameters have been monitored during the simulation: these include: the horizontal displacements and accelerations, with the corresponding shear strains; the cyclic stress ratio *CSR*; the vertical and horizontal stresses; and the excess pore water pressures and related ratio r_u. Values were also recorded elsewhere, such as in the bedrock and at the top of the dikes.

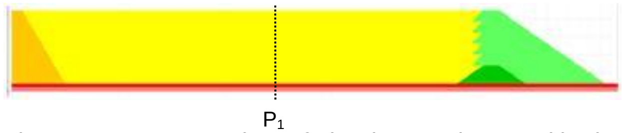

Figure 6. Cross section of the impoundment with the external dikes after six raised steps with the centerline construction method.

The geotechnical parameters and numerical procedures used for these simulations are the same as those presented above for the upstream dikes.

Figure 7 presents the iso-contours of the horizontal displacements within the impoundment, for the centerline-raised dikes.

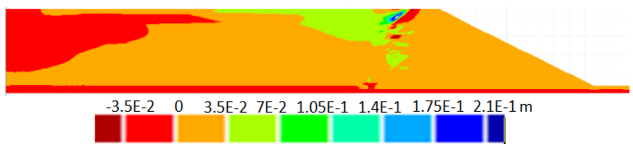

Figure 7. Final deformed geometry and horizontal displacement contours at the end of shaking in the tailings impoundment with a centerline raised dike.

It can be observed that the maximum horizontal displacement in this case is 0.21 m. This is more than 2 orders of magnitude smaller than with the upstream dikes (see Figure 4), which is a clear demonstration that the centerline method leads to largely improved seismic stability.

It is interesting to note also that the value r_u at location P_1 is close to unity (Figure 8), indicating that the tailings have reached liquefaction before the end of shaking. The simulations thus show that the centerline method doesn't affect tailings liquefaction; it can however significantly reduce the lateral displacements of the retained tailings (and associated risk of breach).

It can also be observed that the centreline-raised dikes experienced a 0.03 m displacement inward (negative), in Figure 7. The horizontal displacement thus occurs in the upstream direction (inside the tailing impoundment) following liquefaction (with r_u close to 1). Further investigation is required to assess the potential effect of such (small) inward displacement on the dikes performance.

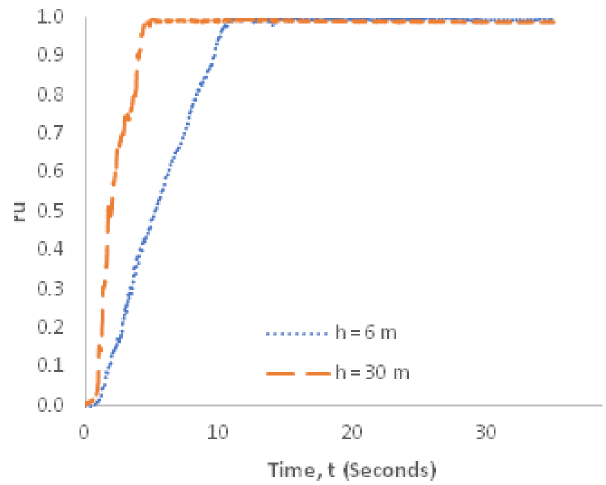

Figure 8. Pore water pressure ratio (r_u) in the tailings impoundment due the seismic loading, after 35 s at location P_1

3.3 Seismic analysis of upstream dikes with waste rock inclusions

The stability of tailings impoundment built with upstream dikes may be compromised by seismic events, as illustrated above. Nonetheless, seismic stability of such type of dikes can be significantly improved by adding strategically placed waste rock inclusions (WRI) (Aubertin et al. 2002, 2019; James et al. 2013, 2017; Ferdosi et al. 2015a). Figure 9 shows a schematic configuration of WRI in a tailings impoundment. The seismic response of the tailings impoundment described above was evaluated in the presence of WRI; the simulations results are shown here for the behavior along section A–A_0.

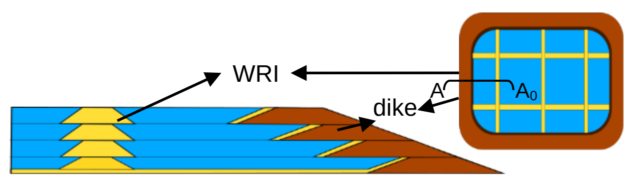

Figure 9. A schematic plan and cross-section views of a tailings impoundment reinforced with WRI (adapted from James et al. 2017).

Figure 10 shows the tailings impoundment with four WRI, each having a width, *W*, of 15 m, with center-to-center spacing, *S*, of 55 m.

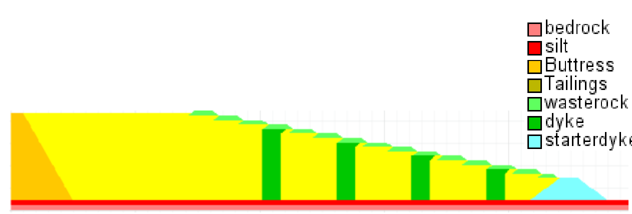

Figure 10. Model of the impoundment with four WRIs (with *W* = 15 m and *S* = 55 m).

Figure 11 shows the maximum horizontal displacements of the external dikes and impoundment with the WRI at the end of shaking. The maximum horizontal displacement of the tailings is still large, up to 6 m, but the highest strains remain confined between inclusions. The maximum displacement of the WRI is 1.5 m in this case. The results show that the WRI can thus enhance the seismic stability of the impoundment by reducing the horizontal displacement.

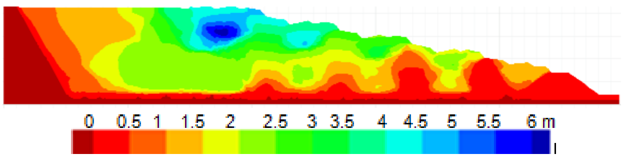

Figure 11. Final deformed geometry and horizontal displacement contours at end of shaking in the reinforced tailings impoundment with four WRI (*W* = 15 m, *S* = 55 m).

Previous simulations results have shown that the number and width of WRI can greatly influence the tailings impoundment response (e.g. James, 2009; Ferdosi et al. 2015b). Additional simulations have been conducted here to specifically assess the impact of the number of WRI on the impoundment seismic behavior.

Figure 12 shows the maximum displacement of an impoundment with five WRI (width *W* = 15 m, center-to-center spacing, *S* = 55 m). This figure can be compared with Figure 4 (no WRI) and Figure 11 (four WRI). The results in Figure 12 indicate that the maximum (local) horizontal displacement after the same earthquake ground motion is reduced to 2 m (from 18 m, and 6 m).

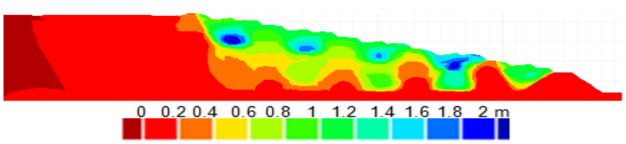

Figure 12. Final deformed geometry and horizontal displacement contours at the end of shaking in the reinforced tailings impoundment with five WRI (*W* = 15 m and *S* = 55 m).

The simulation results also show that WRI do not significantly reduce the generation of excess pore water pressures in the tailings (except for locations very close to an inclusion), but are rather used to limit excessive deformation due to liquefaction (see also James and Aubertin, 2012; Ferdosi et al.2015) .

Finally, Figure 13 shows the horizontal displacement with four WRI, each having a width *W* = 25 m. The results obtained with wider inclusions indicate that the maximum horizontal displacement is about 1.8 m, which is much less than the 6 m obtained with 4 WRI having a width *W* of 15 m

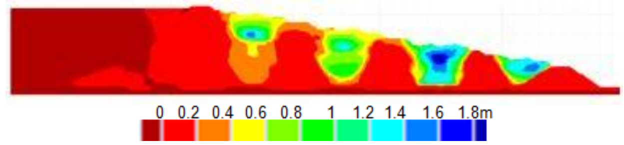

Figure 13. Final deformed geometry and horizontal displacement contours at the end of shaking in the reinforced tailing impoundment with four WRI (*W* = 25 m and *S* = 55 m).

4 DISCUSSION AND CONCLUSION

Numerical dynamic simulation results have been obtained with FLAC and the UBCSAND model to assess the seismic performance of tailings impoundment as a function of dike construction method (upstream and centerline). The analyses show that the horizontal displacements within the tailings impoundment built with the upstream method are much higher than for the centerline method following the same seismic event. These results demonstrate that construction by the centerline method can significantly enhance the seismic response of tailings impoundment compared with the upstream method.

Other simulation results also show that WRI can significantly improve the seismic performance of the tailings' impoundment with upstream dikes by reducing the displacement of the external. The displacements along the upstream slope tend to decrease with an increasing number of inclusions and also with larger inclusions width.

The results presented in this article were obtained by simulating the response of consolidated tailings in the impoundment. As seismic events can also occur during the operation of an impoundment, the seismic response of unconsolidated tailings during deposition is also being investigated as part of the ongoing study. Additional analyses are also being performed for other earthquake ground motions and model characteristics.

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