Effect of mine waste rock inclusions on the consolidation of tailings

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ABSTRACT

Mining of hard rock ore deposits produces granular, cohesionless tailings with a grain size distribution dominated by the silty fraction. The deposition of these tailings as slurry induces a loose state, with high pore-water pressures and low resistance to static and cyclic loadings. Due to the high fines content, the self-weight consolidation of these deposits is a long process. This process can be accelerated through the use of pervious inclusions. This paper presents the results of a numerical investigation of the use of drainage inclusions made of waste rock. These waste rock inclusions, which are much more pervious than the surrounding tailings, facilitate dissipation of the pore-water pressures induced during deposition and thus accelerate consolidation. Results of finite element simulations are presented to illustrate the effects of these inclusions on pore-water pressure dissipation. Additional simulations were conducted to assess the influence of various factors on the response of tailings.

RÉSUMÉ

L'exploitation des gisements miniers en roches dures produit des résidus de faible cohésion ayant une granulométrie dominée par la fraction silteuse. Le transport hydraulique et le dépôt de ces résidus induisent un état lâche, avec des pressions interstitielles élevées et une faible résistance aux chargements statique et cyclique. La consolidation naturelle des résidus sous leur propre poids est un long processus. Cette phase peut être accélérée en utilisant des inclusions drainantes. Cet article présente les résultats d'une étude numérique sur l'utilisation d'inclusions formées de roches stériles pour accélérer la consolidation des résidus miniers. Ces inclusions de roches stériles, qui sont beaucoup plus perméables que les résidus, aident à dissiper la pression interstitielle en excès pendant le remplissage du bassin. Les résultats obtenus à partir de calculs par élément finis sont présentés afin d'évaluer l'effet des inclusions sur le tassement et la dissipation de la pression d'eau. D'autres simulations sont également menées pour évaluer l'influence de divers facteurs sur la réponse des résidus

1. INTRODUCTION

There have been several failures of tailings impoundments over the last few decades. The associated flow of liquefied material has resulted in loss of life as well as environmental and economic damage. The risk of failure can be reduced by applying a co-disposal technique consisting of placing waste rock inclusions (WRI) within an impoundment, prior to and during tailings deposition, as shown on Figure 1 (Aubertin et al. 2002; James and Aubertin 2009, 2010). The waste rock is used to create continuous inclusions (internal dykes) or isolated heaps within the impoundment to provide additional drainage to accelerate consolidation and reinforcement, thus increasing the stability of the tailings. Some of the potential benefits of this method have been confirmed by laboratory tests on a seismic simulator (Pépin et al. 2009) and by numerical simulations of tailings impoundments with and without WRI under cyclic loadings (James 2009).

This paper presents a numerical modeling investigation of the use of waste rock inclusions to accelerate the consolidation of slurry-deposited tailings through the dissipation of pore-water pressures (PWP). An objective of this study was to assess some of the factors that influence the dissipation of PWP in the impoundment during tailings deposition.

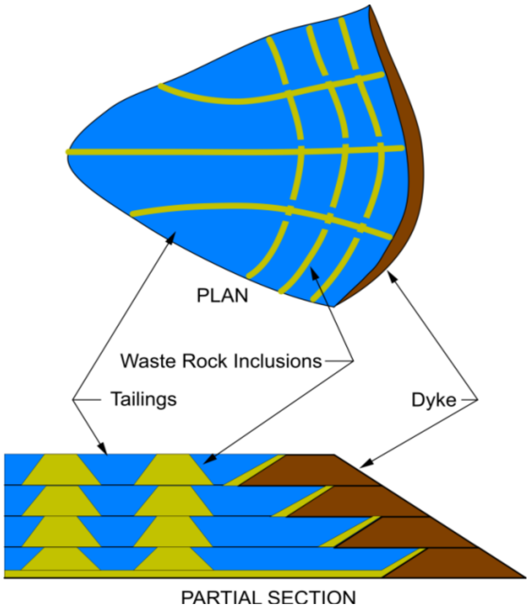

Figure 1: Schematic illustration of a tailings impoundment with waste rock inclusions placed prior to and during tailings deposition (Adapted from James and Aubertin 2010).

2. HORIZONTAL CONSOLIDATION SOLUTIONS

The placement of pervious inclusions in fine-grained soils generally results in a change from consolidation induced by vertical drainage to consolidation induced by horizontal drainage.

Vertical drains are commonly used to accelerate the consolidation of fine-grained soils by providing a reduced (radial) drainage path. Baron (1948) and Hansbo (1981) provided analytical solutions for the radial drainage of a unit cylindrical cell under axisymmetric, equal strain conditions, with the possibility of considering the finite permeability of the drain and smear zone. More recently, Chin (2004) solved the equal strain consolidation problem around cylindrical drains by considering coupled vertical and radial drainage with progressive surface loading.

The use of gravel drains (stone columns) has also been investigated for fine-grained soils (e.g. Barksdale and Bachus 1983; Han and Ye 2001, 2002). The higher stiffness of these drains affects the stress distribution in the adjacent soil, which also affects the rate of consolidation.

Hird et al. (1992), Indraratna and Redana (1997, 2000), and Tan et al. (2005, 2008) extended the equivalent unit cell solution to convert the axisymmetric expressions into two equivalent plane strain solutions. Such conversions can be accomplished by correcting the soil hydraulic conductivity or the drain width to take into account the difference in the (equivalent) drainage area.

The results from two-dimensional numerical modeling, under plane strain conditions have also been used to assess the behaviour of fine-grained soils with vertical drains (Indraratna and Redana 2000).

The numerical simulations presented in this paper consisted of plane strain analyses of the effect of WRI on the consolidation of tailings. Some of the results presented here have been successfully compared with the above mentioned analytical solutions (Jaouhar 2011).

3. NUMERICAL MODELLING APPROACH

Version 2007 of the SIGMA/W finite element program (Geo-Slope Inc.) is used to simulate the response of a tailings deposit assuming the geometry shown on the left side of Figure 2.

The deposit consists of tailings with WRI. The inclusions were assumed to be placed at the same time as the tailings, assuming a filling rate of 2 m/year for 10 years resulting in a 20-m-high deposit. The water table was maintained at the tailings surface where the pore-water pressure (PWP) is fixed at 0. Each year, a 2-m-thick layer of saturated tailings was placed instantaneously and the PWP was allowed to dissipate until the placement of the next layer. The tailings are underlain by a stiff, impervious foundation layer. The reference width of each WRI was 6 m, and these were spaced 20 m apart (or 26 m center-to-center).

A numerical model representative of a large scale impoundment requires a large mesh, with thousands of elements, which would require considerable calculation time and could render convergence difficult. The symmetry of the problem analyzed allows a reduction of the model size by representing only a portion of the impoundment, as shown in Figure 2a; the validity of this simplification was assessed by comparing the response of the complete model and that of the reduced-size model (Jaouhar 2011).

Three types of materials were considered: tailings, waste rock (inclusions) and a foundation layer. Rectangular elements were used for the tailings (0.4 m wide and 0.15 m in height); the waste rock was modeled using 0.15-m-square elements; and foundation layer was modeled using both 0.15-m-square and 0.4 m (W) by 0.15 m (H) rectangular elements.

The elastic-plastic Mohr-Coulomb constitutive model was used to represent the behaviour of the tailings and waste rock. Five input parameters were required: Young's modulus (E) and Poisson's ratio (ν) for elasticity, angle of internal friction (ϕ'), cohesion (c'), and angle of dilation (ψ) for plasticity. The linear elastic model was used for the foundation layer. Table 1 presents the values used in the analyses.

The mechanical boundary conditions of the reference model shown in Figure 2a were as follows: the base of the model was fixed with respect to vertical and horizontal displacements (stiff foundation); the left and right sides of the model were fixed with respect to horizontal displacements (lines of symmetry). As mentioned above, successive layers of tailings are added on the upper surface, which was free draining. No flow was permitted across the sides or base of the model.

The effect of a smear (or transition) zone has been ignored in the calculations presented here (this aspect is considered in other simulations presented in Jaouhar 2011). A few calculations have also been conducted with the model shown in Figure 2b, with a geometry that is more representative of the WRI (see Fig. 1). The main results presented below refer to the excess PWP at locations A, B, C, and D (shown in Fig. 2b).

As mentioned previously, the reference model included 6 m wide inclusions spaced 26 m apart. The saturated hydraulic conductivity, k was equal to 10^{-7} m/s and 10^{-4} m/s for the tailings and waste rock respectively; k was assumed to be isotropic (k_v/k_h=1). The parameters values for the reference model are shown in Table 1.

To evaluate the effect of different factors that may influence the consolidation rate of tailings with WRI, additional simulations were conducted with the parametric values given in Table 2. Results of these calculations follow.

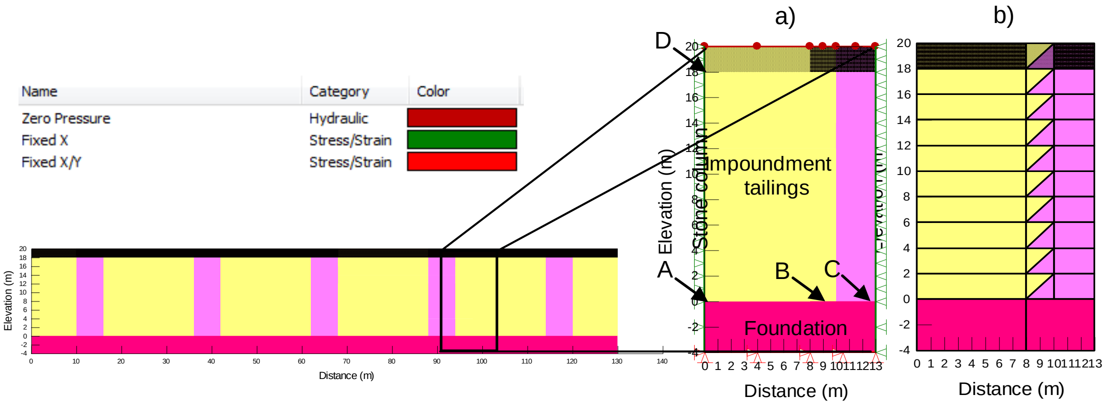

Figure 2: The impounded tailings (left) with waste rock inclusions; (a) Isolated section used in the simulations, with the boundary conditions and locations of the (numerical) observations (b) Geometry of the model with WRI represented by small successive raises, with a portion resting on the tailings.

Table 1. Material parameters for the reference model.

materials	model	γ_{sat} (kN/m^3) Saturated unit weight	ϕ' Friction angle	ν Poisson's ratio	ψ Dilation angle	c' (kPa) Cohesion	k_{sat} (m/s) Hydraulic conductivity	E (MPa) Young's modulus
Tailings	Elastic plastic	23.75	33°	0.3	10°	0.5	10^{-7}	10
WRI	Elastic plastic	23.75	37°	0.3	0°	0	10^{-4}	500
Foundation	Linear elastic	20.0	-	0.334	-	-	10^{-14}	$5x10^5$

Table 2. Values used for the parametric study calculations (adapted from Bussière 2007 and James 2009).

	Reference model parameters	Parametric study parameters			
Inclusions edge spacing (m)	20	10	30	50	100
$E_{Tailing}/E_{Inclusion}$	0.02	0.1	0.01	0.001	
Drain width (m)	6	8	10		
k_v Tailings (m/s)	10^{-7}	10^{-6}	10^{-8}		
k_h/k_v (Tailings)	1	10	100		
$k_{Tailing}/k_{Inclusion}$	0.001	0.1	0.01		
Shape of inclusions	Conventional	Irregular			

4. MAIN RESULTS

4.1 The Reference Case

The reference case was represented by Fig. 2 (a) and the reference model parameters given in Tables 1 and 2.

Figure 3 shows the dissipation of pore-water pressures (PWP) at three locations (A, B and C) indicated in Fig. 2a, in the tailings and waste rock inclusion. These results show that upon placement of the 10th tailings layer, the PWP at the base of the tailings reaches a maximum of 224.1 kPa, which corresponds to the equilibrium (hydrostatic) PWP for the first nine layers (i.e. 18 m of water, or 176.6 kPa) plus the pressure due to the total weight of the tenth layer (i.e. 47.5 kPa). The excess PWP then progressively dissipates until the hydrostatic condition is reached (i.e. PWP of 196.2 kPa). The results also indicate that the consolidation associated with the dissipation of excess PWP in the tailings occurs faster for the location closer to the WRI (B vs A) and the dissipation in the inclusion itself (C) is very rapid.

Figure 4 shows the distribution of the vertical strain, effective vertical stress and pore-water pressure in the tailings and WRI after the 10th layer is added. These isocontours indicate that the WRI affects the stress and strain fields, because of its higher stiffness (compared with the tailings). There is a stress transfer from the tailings to the WRI, due to the larger deformation of the tailings under their own weight, which is resisted by the friction at the contact with the waste rock. This reduces the vertical strain in the tailings close to the WRI, while it increased the vertical stress in the latter. This stress redistribution also plays a role in the way the effective stresses evolve as a result of the excess PWP dissipation.

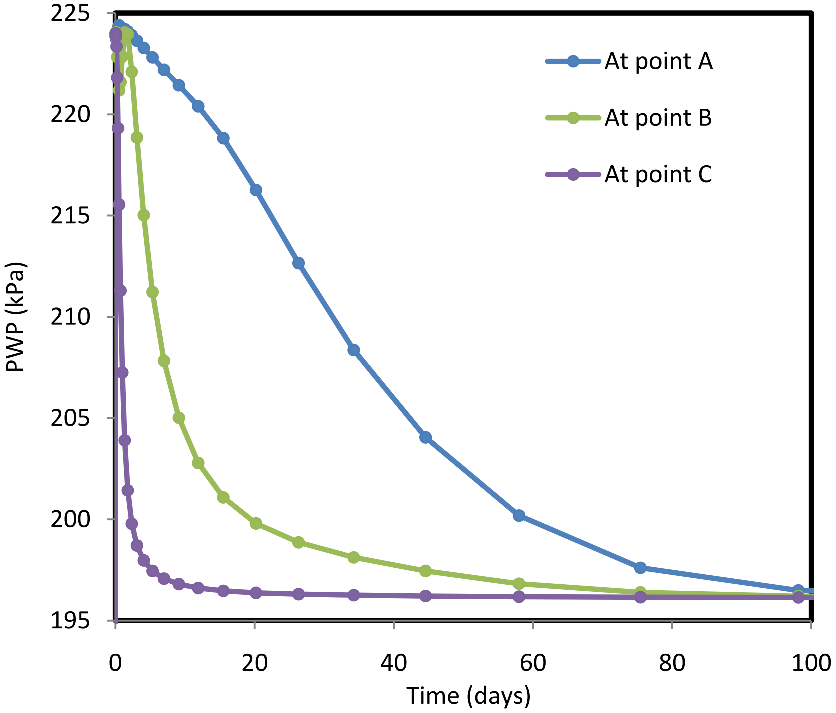

Figure 3: Evolution of the PWP over time, at 3 locations in the tailings (A and B) and in the WRI (C) after the 10th layer is added; reference model shown in Figure 2a, with parameters given in Table 1.

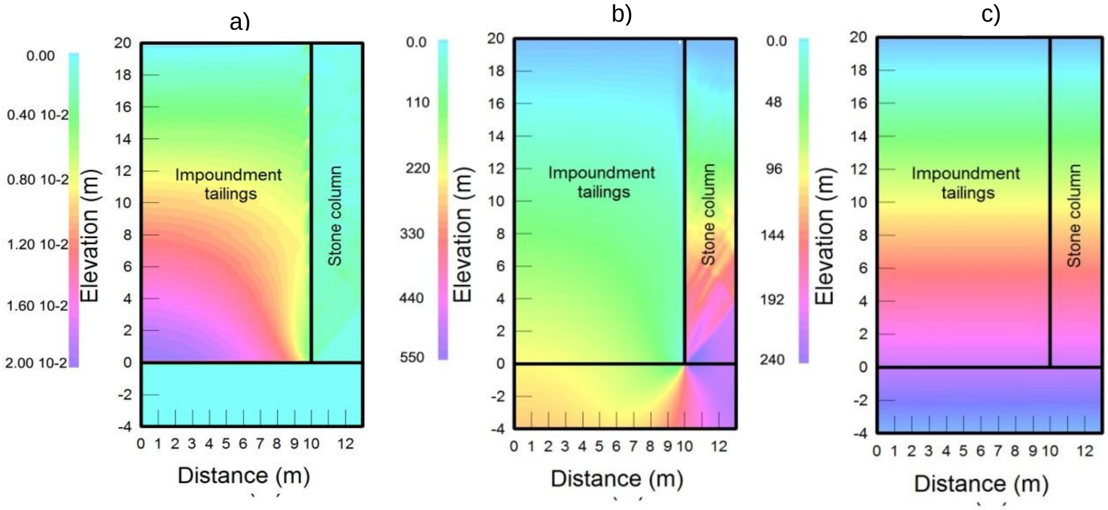

Figure 4: Distribution of a) Vertical strain, b) Effective vertical stress, and c) Pore-water pressure in the impoundment (reference model) just after the 10th layer is added.

The simulations, presented below, have been conducted by varying some of the parameters (defined in Table 2) to assess their respective influence on the behaviour of tailings with WRI.

4.2 Spacing of the WRI

One of the major factors affecting the consolidation process is the spacing of the WRI in the tailings impoundment. Figure 5 shows the effect of this spacing on the excess PWP at point A (for the 10th layer). The results indicate that when the spacing is large (100 m), the behaviour of the tailings is the same as for the case without WRI. The rate of consolidation increases with decreasing spacing (from 100 m to 10 m), due to the shorter drainage path. This means that as the spacing between inclusions is reduced, the rate of consolidation is affected more by the horizontal drainage than the vertical drainage.

4.3 Size of the WRI

As seen in Fig. 6, the width of the WRI has a limited effect on the rate of consolidation of the tailings (for the reference spacing of 26 m center-to-center). An increase of the inclusion width (from 6 m to 10 m) has only a minor effect on the rate of consolidation. The increased width of the WRI leads of a minor shortening of the drainage path.

4.4 Hydraulic conductivity of the tailings and WRI.

A reduction of the hydraulic conductivity of the WRI may be induced by various processes, including material densification or by the migration of tailings into the coarser waste rock during deposition and consolidation. As a result, it can be expected that the rate of consolidation would be reduced. This is shown in Figure 7, which illustrates the effect of changing the ratio of the hydraulic conductivity of the tailings and of the WRI (k_T/k_{WRI}) by two orders of magnitude. The effect is more pronounced farther from the inclusion, as seen by comparing Fig. 7a (at location A in Fig. 2) and Fig. 7b (at location B).

Consolidation and PWP dissipation is also affected significantly by the hydraulic conductivity of the tailings, as shown in Figure 8 (for locations A and B). For instance, when $k_T=10^{-8}$ m/s, the total dissipation of excess pore-water pressure requires about 200 days (for the reference case). This period is reduced to about 3 days for $k_T=10^{-6}$ m/s. This indicates that the rate of consolidation and the performance of WRI largely depends on the hydraulic conductivity of the tailings.

4.5 Tailings anisotropy (of k)

As shown in Figure 9, a variation of the ratio of the horizontal to the vertical hydraulic conductivities, (k_h/k_v) from 1 to 100 (with k_h being constant did not have a significant effect on the PWP dissipation at locations A and B. As PWP dissipation is largely dominated in this case by horizontal drainage, the role of vertical drainage is very limited (for these conditions). The important factor is thus the value of k_h rather that the ratio k_h/k_v. However, the dissipation rate closer to the surface (at location D; see Fig. 2a) was influenced significantly by the ratio k_h/k_v, as seen in Fig. 9c; this behaviour is consistent with the proximity to the drainage surface that increases the contribution of vertical drainage.

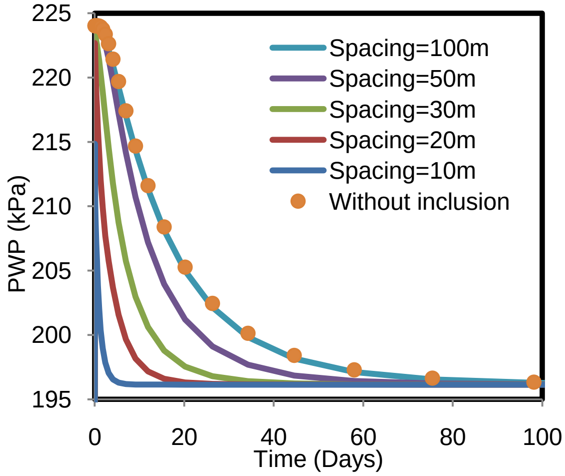

Figure 5: Development of the pore-water pressure after the 10th layer is added, for different spacing between WRI (values of PWP given at point A).

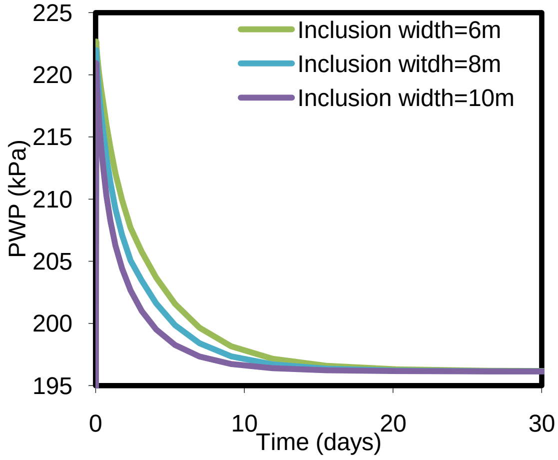

Figure 6: Evolution of the pore-water pressure after the 10th layer is added at point A for different width of the WRI.

4.6 Young's modulus of the WRI

One of the major differences between stone (gravel) columns (or WRI) and sand drains is that the former have a much higher stiffness when compared within that of the consolidating medium (i.e. tailings). This large stiffness influences, to a certain degree, the stress distribution in the zone near (and inside) the WRI (as illustrated in Fig. 4). However, a realistic variation of Young's modulus, E (represented here by changing the ratio of E for the WRI and tailings) has a very limited effect on the rate of consolidation, as shown in Fig. 10. This means that as far as PWP dissipation is concerned, the WRI stiffness only plays a minor role.

The effect of this stiffness (and strength) may however play a major role on the reinforcement provided by the WRI in the case of a seismic event causing liquefaction of the tailings (James 2009).

4.7 Shape of WRI

Fig. 2 (b) shows a more realistic shape, which has been used to simulate the response of tailings with WRI. The results presented in Fig. 11 indicate that this shape has a moderate effect on the time required to dissipate the pore-water pressure in the vicinity of the WRI (at point B); there is no effect of the shape when moving farther from the WRI (at point A, not shown here).

It can be expected that the actual shape of WRI constructed in an impoundment during tailings deposition will be more irregular than the idealised vertical (wall-like) shape used in the above calculations (e.g. see Fig. 1).

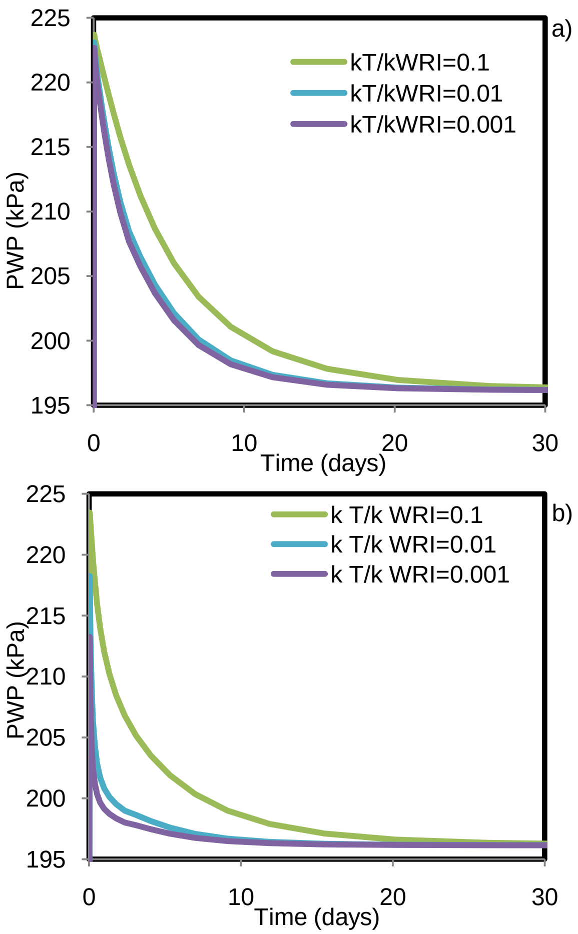

Figure 7. Effect of the hydraulic conductivity (k) ratio (tailings/waste rock) on the evolution of the pore-water pressure after the 10th layer is added a) at point A, and b) at point B.

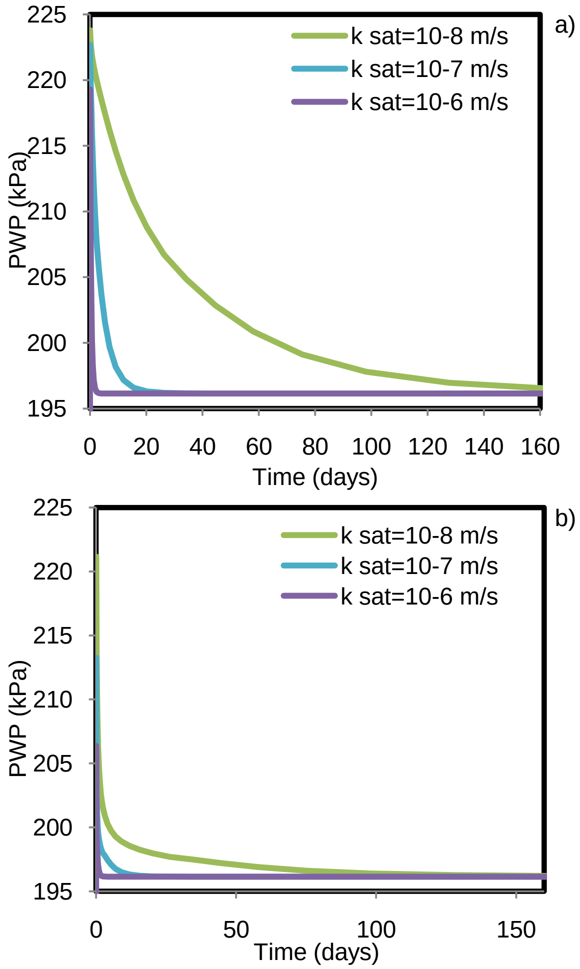

Figure 8. Effect of the tailings hydraulic conductivity on the PWP evolution after the 10th layer is added a) at point A, and b) at point B.

1 DISCUSSION AND CONCLUSIONS

Numerical analyses, conducted with the finite element code SIGMA/W, on a portion of a tailings impoundment with waste rock inclusions indicate that the presence of WRI accelerates the consolidation of the tailings in the impoundment.

The parametric simulations of the impoundment also revealed that, for the conditions assessed here, the width of the WRI, the hydraulic conductivity ratio of the tailings to the WRI, the Young's modulus of the WRI, and the anisotropy of the tailings have a limited to negligible influence on the rate of consolidation in the impoundment. However, for these same conditions (see Tables 1 and 2), the spacing of the inclusions and the horizontal hydraulic conductivity of the tailings had a significant influence on the consolidation rate.

The use of waste rock inclusions may result in a significant improvement in the performance of the tailings impoundment, by accelerating the PWP dissipation and

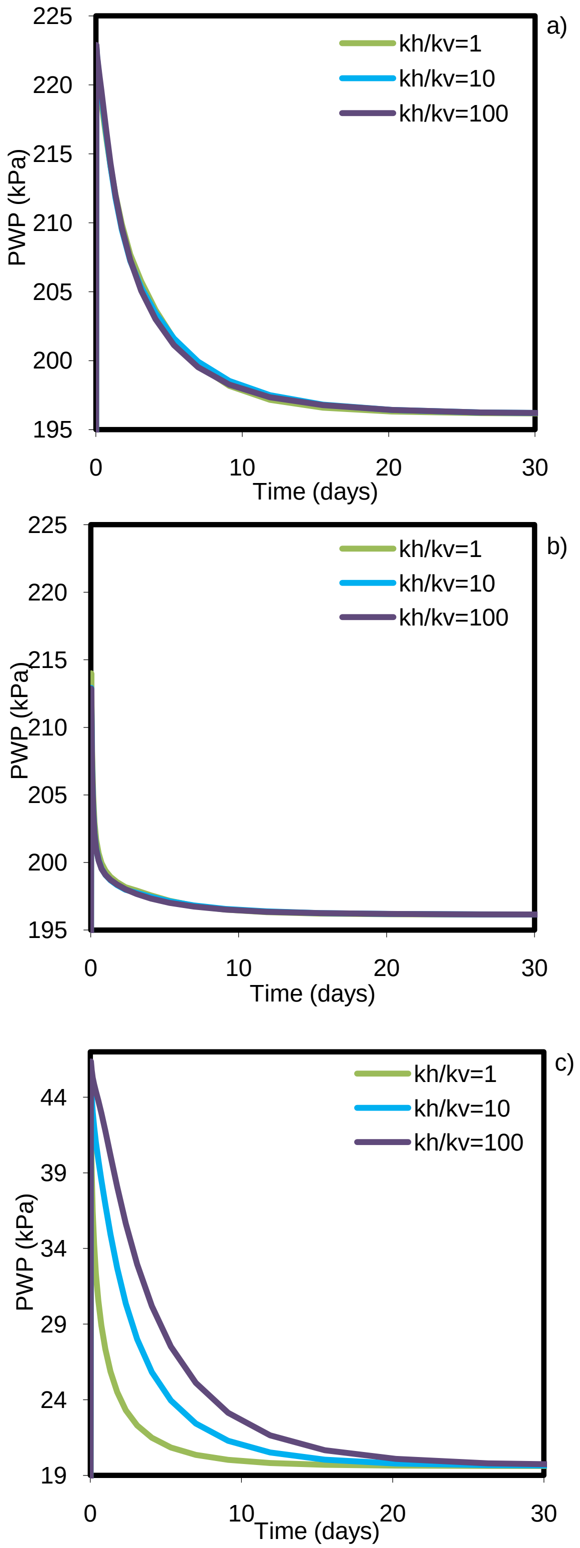

Figure 9. Effect of the k_h/k_v ratio for the tailings on the evolution of the pore-water pressure after the 10^{th} layer is added a) at point A, b) point B, c) and at point D.

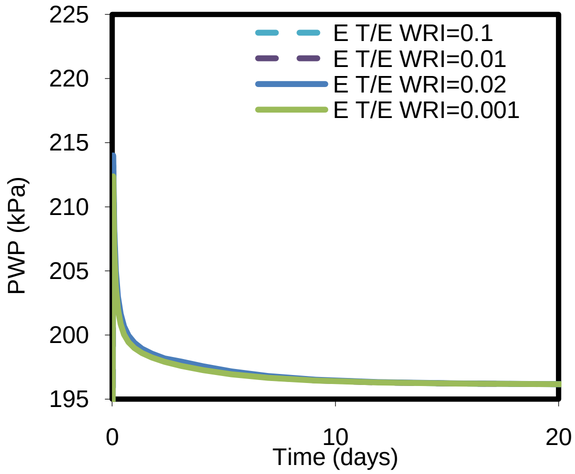

Figure 10. Effect of the Young's modulus ratio on the evolution of the pore-water pressure after the 10th layer is added at point B.

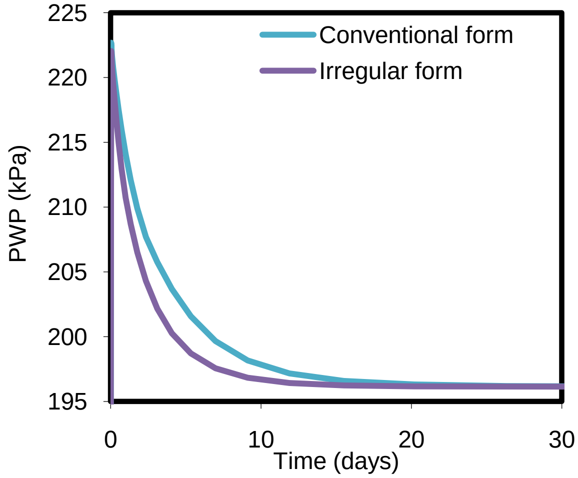

Figure 11. Effect of the shape of the WRI on the evolution of the pore-water pressure after the 10^{th} layer is added at point A.

associated consolidation of the tailings.

The use of WRI in a tailings impoundment is being investigated for a new mining site and field testing of the WRI concept will commence soon. The results obtained in situ will be very useful in validating the simulations presented here and in improving our understanding of this technique.

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