An experimental study of tailings migration through waste rock inclusions

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ABSTRACT
Waste rock inclusions (WRI) placed in tailings impoundments aim at improving surface disposal of mine wastes. WRI can provide several operational advantages, increase impoundment stability and reduce the consequences of a dike failure. More specifically, WRI favor the dissipation of excess pore water pressures and accelerate tailings consolidation. They also add rigidity to tailings impoundments and increase their physical resistance against static and dynamic loadings. However, under a hydraulic gradient, tailings and fine particles of waste rock can move through the pores formed by larger waste rock particles, and this may affect the drainage capacity of inclusions. The hydraulic gradient generated by tailings deposition or by a change in phreatic conditions may initiate such particles movement. This research project evaluates the hydro-geotechnical behaviour of WRI with a focus on the migration of fine grained particles under various conditions. The effects of hydraulic gradients, initial tailings (slurry) density, deposition sequence, and waste rock gradation were assessed experimentally using tests in large-diameter instrumented columns. The experimental procedures are described and representative results are presented and discussed in this article.

RÉSUMÉ
Les inclusions de roches stériles (IRS) placées dans un parc à résidus visent à améliorer la disposition des rejets miniers entreposés en surface. Les IRS peuvent apporter des avantages opérationnels, améliorer la stabilité des ouvrages et réduire les conséquences d'une éventuelle rupture de digue. Plus spécifiquement, les IRS favorisent la dissipation des pressions interstitielles en excès et accélèrent la consolidation des résidus. Elles apportent aussi une plus grande rigidité aux parcs à résidus et une stabilité physique accrue face aux sollicitations statiques et dynamiques. Toutefois, sous un gradient hydraulique, les résidus et la partie fine des stériles peuvent migrer à travers les pores formés par les grains grossiers des roches stériles, ce qui peut affecter la capacité de drainage des inclusions. Le gradient hydraulique généré par la déposition des résidus ou par un changement des conditions phréatiques peut déclencher un tel mouvement des particules fines. Ce projet de recherche évalue le comportement hydrogéotechniques des inclusions avec une emphase sur la migration des particules fines sous diverses conditions. Les effets du gradient hydraulique, de la densité initiale de la pulpe de résidus, de la séquence de déposition et de la granulométrie des stériles ont été évalués expérimentalement à partir d'essais menés dans des colonnes verticales instrumentées de grand diamètre. Les procédures expérimentales et certains résultats représentatifs sont présentés et discutés dans cet article.

1 INTRODUCTION

The mining industry produces large quantities of tailings and waste rocks. Tailings are usually transported hydraulically to surface impoundments while waste rocks are typically stored in surface piles (e.g. Aubertin et al. 2002a). The hydro-geotechnical properties of waste rocks and tailings, including grain size, stiffness and compressibility, shear strength, hydraulic conductivity and water retention capacity, are very different. These differences can be used to improve disposal practices.

The tailings and waste rock co-deposition technique known as waste rock inclusions (WRI) in impoundments was initially proposed over fifteen years ago (Aubertin et al. 2002b; James et al. 2013). The objective of this technique is to better manage the large amount of mine wastes stored on the surface. Physical laboratory models (Pépin 2010; Saleh Mbemba 2016) and numerical simulations (James 2009; James and Aubertin 2010, 2012; L. Bolduc, 2012; Jaouhar 2012; L.Bolduc et al. 2014; Ferdosi et al. 2015; Saleh Mbemba 2016) have shown that the use of waste rock inclusions can accelerate the dissipation of excess pore pressures and improve the stability of tailings dikes during static and dynamic loadings. WRI are currently constructed at the Canadian Malartic mine (Figure 1), and some of these are monitored to assess their influence on tailings behavior (James et al. 2017).

One of the key issues with WRI is the migration of tailings through waste rock pores, which could lead to the formation of a transition zone close to the interface. Tailings intrusion may then reduce the hydraulic conductivity of the waste rock inside the inclusion near the interface, in the affected zone. Migration of tailings and of fine particles of waste rock could be initiated by the hydraulic loading induced by the deposition of tailings slurry or by a change of groundwater level. The rate of dissipation of excess pore water pressures can then be decreased if the voids of the waste rock are blocked (clogged) by these fine particles. In some cases, additional water pressures may also develop near the interface if the local hydraulic conductivity decreases critically.

As waste rocks have a very widely graded particle size distribution, they may be subjected to internal particles movements under critical hydraulic gradients. The migration of fine particles through the pores of waste rock has been reported by various authors (e.g. Morin and al. 1991; Aubertin et al. 2002a; Peregoedova et al. 2013).For example, Peregoedova (2012) has conducted permeability tests in large size instrumented columns. These tests showed that migration of fine particles in waste rock was initiated under a hydraulic gradient comprised between 2 and 3 (with a relatively high flow velocity). In this case (grain size D ≤ 5 cm), the maximum size of the exfiltrated particles reached up to 400 µm. Such movement of fine particles could clog pores locally while increasing porosity elsewhere, thus creating preferential flow paths and varying saturated hydraulic conductivity (e.g. Reddi et al. 2000; Massei et al. 2002; Benamar et al. 2005; Alhaddad et al. 2008; Peregoedova, 2012).

Figure 1. One of the waste rock inclusions in the tailings impoundment at the Canadian Malartic Mine (in 2017)

The risk for fine particles movement in pores may be assessed using self-filtration criteria, such as those presented by Kezdi (1969), Sherard (1979) and Kenney and Lau (1985). Chapuis (1992) has shown that these criteria can be simplified as summarized in Table 1. Kezdi (1969) and Sherard (1979)'s methods consider that coarse particles cannot stabilize fine particles if the grain size curve slope is less than 24.9 % and 21.5% per logarithmic cycle, respectively. With the Kenney and Lau (1985) method, the slope S of fine fraction grain size curve should be greater than 1.66 × F per log cycle, where F is the mass percentage of the free particles (fines) having a diameter smaller than D (mm).

Fine particles can start moving due to critical hydraulic conditions. For a uniform sand or a non-plastic silt formed of rounded particles, the critical gradient i_c can occur when effective stresses are reduced (close) to zero due to flow forces (Holtz and Kovacs, 1980). This type of behavior is mostly observed for unconfined natural soils with a relatively uniform distribution (Chapuis, 2009). Terzaghi (1943) proposed a theoretical expression to define the critical gradient for saturated uniform sands (and non plastic silts):

$$i_c = \frac{\rho'}{\rho_w} = (1 - n)(D_r - 1) \qquad [1]$$

where, ρ' (kg/m^3) and ρ_w (kg/m^3) are the buoyant soil and water densities, respectively; D_r is the relative density of the solid grains; n is the porosity of the material (-).

Table 1-1 : Commonly used filter criteria (adapted from Chapuis, 1992)

	Filter criteria (for stable materials)	**Chapuis (1992) Representation (for stable materials)**
Kezdi (1969)	$D_{15}/d_{85} < 4$	$S = \frac{0,15}{\log I_r} > 24.9\%$
Sherard (1979)	$D_{15}/d_{85} < 5$	$S = \frac{0,15}{\log I_r} > 21.5\%$
Kenney and Lau (1985)	H/F=1 H =F_{4D} - F_D F < 0.20	$S > 1.66F\%$ For : F = 5 % S > 8.3% F = 10 % S > 16.6% F = 15% S > 24.9% F = 20 % S > 33.2%

S: slope of the grain size distribution curve for the portion F < 20%; I_r : degree of instability of a soil equal to D_{15} (filter) / d_{85} (soil to be protected); d_{15} and d_{85} are particle diameters corresponding to 15% and 85% of passing by mass, respectively.

Typical values of i_c are comprised between 0.7 and 1. Skempton and Brogan (1994) reported that unstable sandy gravels showed i_c values between 0.2 and 0.34 for internal erosion. These values were lower than those given by Equation 1. Skempton and Brogan (1994) proposed the following expression for the critical hydraulic gradient, i_c, of fine sandy particles inside gravel pores:

$$i_c = \alpha \frac{\gamma'}{\gamma_w} \qquad [2]$$

where γ' (kN/m^3) and γ_w (kN/m^3) are the buoyant (effective) and water unit weights, respectively; α is a reduction factor for the effective stresses transferred to the fine fraction.

Riffon (2005) investigated migration between fine- and coarse-grained materials using laboratory models to assess the movement of particles at the interface between a layer of silt (silica) and a coarser granular material (sand). Filtration test results indicated that particles movement was not clearly identified. In these tests, the observed hydraulic conductivity variations appeared to be caused mainly by settlement (and change of porosity) rather than by particles migration.

Rey et al. (2014) have conducted an experimental study of tailings migration into waste rock (0-20 and 0-50 mm) in an instrumented vertical column and the effect on saturated hydraulic conductivity in a multilayer cover. The results indicated that the migration of fine particles was more pronounced for coarser waste rock (0-50 mm) ; only a slight decrease of the saturated hydraulic conductivity of the waste rock, from 3 × 10^{-2} to 2 × 10^{-2} cm/s, was observed when the tailings solid content P (pulp density) was relatively low (≤ 65%).

This article describes some of the work conducted to evaluate the movements of waste rock fine particles and tailings through the relatively large pores of waste rock, and their effect on WRI performance based on the measured hydraulic conductivity and drainage capacity. Laboratory tests were conducted in large size instrumented columns (30 cm in diameter). The effects of hydraulic gradient, tailings pulp density, deposition sequence and retention mechanisms were evaluated experimentally.

2. TAILINGS AND WASTE ROCK PROPERTIES

Fine-grained tailings and waste rock were sampled at the Canadian Malartic gold mine, located in Abitibi, Québec, and characterized in the laboratory. The waste rock fraction 0-50 mm was selected to assess the internal migration of waste rock fine particles under various hydraulic loadings in instrumented columns, based on the previous study of Peregoedova (2012) and the column internal diameter (D of 30 cm).

Particle size analyses were performed according to ASTM D7928-17 (2017), with sieving for coarser grains (> 75 μm) and hydrometer (sedimentation) measurements for the finer fraction. The values of D_{10}, D_{30}, D_{50} and D_{60} of the waste rock (0-50 mm) are 2.04, 12.3, 24.6 and 30.64 mm, respectively (Figure 2). These values are fairly similar to those reported by Bussière et al. (2011) and Peregoedova (2012). Waste rock solid grain relative density D_r was measured according to ASTM C127-15 (2015). The average D_r for waste rock is 2.80, which is in the range of values reported for waste rock by Gamache-Rochette (2004) and McLemore et al. (2009).

Permeability tests with constant hydraulic head were conducted on the waste rock in an instrumented column following ASTM D2434-06 (2006) and the detailed laboratory protocol presented by Peregoedova (2012). Saturated hydraulic conductivity k_{sat} of the waste rock 0-50 mm (porosity n ~ 0.3) was measured under low hydraulic gradients (i < 0.03); the experimental k_{sat} values are near 1 cm/s. These measured values are fairly close to those obtained from the KC (Chapuis and Aubertin, 2003) and KCM (Mbonimpa et al. 2002) predictive models.

The D_{10} and D_{60} values for the tailings are 0.0043 mm and 0.040 mm (Figure 2), respectively. These values are in the typical range reported by Bussière (2007) for hard rock mine tailings. These tailings are classified as non-plastic inorganic silts (ML) according to ASTM D2487 – 17 (2017) (Unified Soil Classification System). The relative density of the grains was measured according to the ASTM D854-02 (2002) standard. The average D_r value is 2.72, which is typical for gold mines (Aubertin and al. 1996; 2002a; Bussière 2007). The saturated hydraulic conductivity k_{sat} was measured with flexible wall permeability tests (ASTM D5084-00, 2000). The average value of k_{sat} obtained for tailings is about $3×10^{-5}$ cm/s for a void ratio e = 0.70. This value is compatible with those reported for similar tailings (e.g., Bussière 2007; Boudrias 2018).

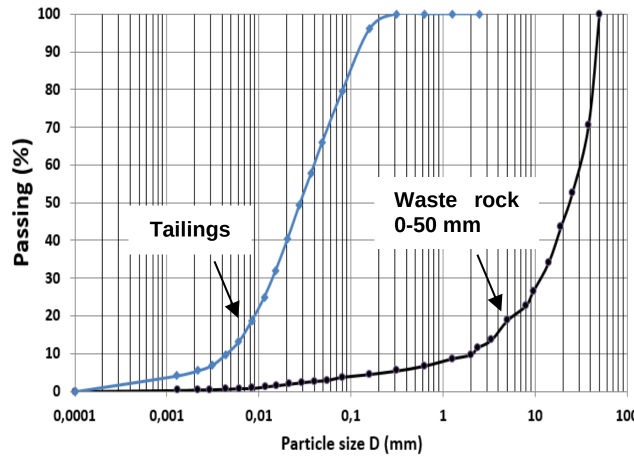

Figure 2. Grain size distribution curves for the tailings and waste rock (0- 50 mm) used in the testing program

3. EXPERIMENTAL SETUP

3.1 Movement of fine particles in waste rock

Column tests were conducted under different hydraulic loadings on the waste rock fraction 0-50 mm to assess fine particles movement (Figure 3). A plexiglas column (height H = 110 cm, internal diameter D = 30 cm) was filled with waste rock to a height of 78 cm. A constant hydraulic head with downward flow was applied. The column was instrumented with pore water pressure (PWP) sensors and piezometers. A funnel was placed inside the column, at the base of the waste rock, to collect fine particles. Fines particles were also collected in the leachate at the exit of the column. The pressure heads used to calculate hydraulic gradients were measured between the piezometers installed along the height of the column (Figure 3).

The waste rock was placed in the column in 12 layers, 6 cm thick. Waste rock was placed to avoid initial segregation and then slightly compacted using a manual hammer. Piezometers and PWP sensors were installed at different positions inside the column to monitor spatial and temporal distributions of pressure heads and pore water pressures, respectively. The waste rock was saturated for several weeks (under a low flow rate) until the degree of saturation, S_r, was close to 97% (as suggested by Chapuis, 2004).

Constant head permeability tests (ASTM D2434) were conducted with a downward flow to evaluate the saturated hydraulic conductivity of waste rock, initially under low hydraulic gradients (i < 0.2) (Adel et al. 1988; Chapuis et al. 2007; Peregoedova 2012). The hydraulic gradient, measured using piezometers, was then gradually increased up to 0.44 to exceed the critical gradient and evaluate the self-filtration capacity of waste rock and identify the fine particles fraction that is most susceptible to move. PWP and flow rates were also measured. Waste rock particle size analyses were performed after dismantling. The results were assessed using the filter criteria in Table 1.

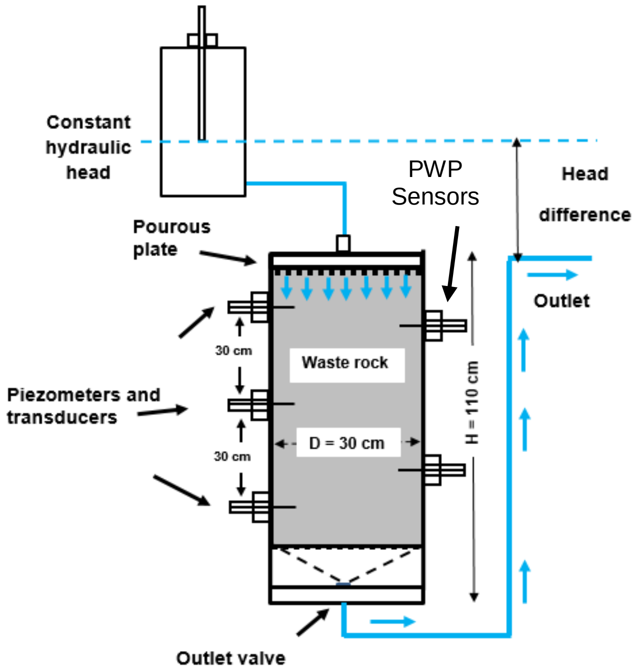

Figure 3. Experimental setup for instrumented column tests on waste rock (adapted from Peregoedova, 2012)

3.2 Movement of tailings through waste rock

Specific tests were also conducted to assess the movement of tailings through waste rock (0-50 mm) pores in the instrumented column. These tests aimed to evaluate the effects of tailings pulp density, deposition sequence, tailings retention in waste rock pores, waste rock grain size distribution, and hydraulic gradients on waste rock hydraulic conductivity drainage capacity. The results from these tests, obtained on a saturated waste rock 0-50 mm (porosity n = 0.3), are presented below.

For each test, tailings were prepared at an initial water content w_0 close to 52%, and initially homogenized and saturated in a cell (Poncelet, 2012). The pulp density, P, can be determined using the following equation (where w is the water content):

$$P = \frac{1}{1 + w} x\ 100 = \frac{1}{1.52} x\ 100 = 66\% \quad [3]$$

Test 1 consisted of three sequences of hydraulic tailings deposition on the surface of saturated waste rock (0-50 mm). The tailings were deposited (low flow) using a pump and with the outlet valve open at the bottom of the column (Figure 4) to simulate progressive filling and evaluate retention (or clogging) mechanisms. The valve installed at the bottom outlet was closed during tailings deposition in Test 2 (identical to Test 1 otherwise). Permeability tests with a constant hydraulic head (ASTM D2434) were performed for both tests after the deposition of saturated tailings in the column. The actual degree of saturation S_r of the waste rock was initially close to 96% during these tests.

The hydraulic gradient in the column was gradually increased from 0.02 to 0.44. The objective was to evaluate the effect of tailings migration on the waste rock hydraulic conductivity and drainage capacity, and to assess the critical gradient for each fraction. Pore water pressures and flow rates were monitored during each hydraulic loading step. The materials in the column (waste rock and tailings) were divided into several layers upon dismantling and their grain size distribution curve was measured.

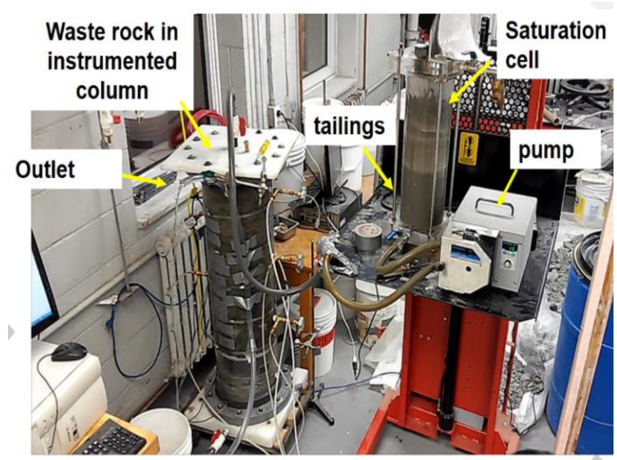

Figure 4. Experimental setup for the deposition of tailings on the surface of waste rock (0-50 mm) in an instrumented column used to investigate tailings migration.

4. RESULTS

4.1. Movement of fine particles in waste rock

Permeability tests were conducted on waste rock in the instrumented column with various gradients. The saturated hydraulic conductivity value measured under low gradients (between 0.02 and 0.03) was comprised between 1.4 and 1.8 cm/s. These values are fairly similar to those given by the KCM (Mbonimpa and al. 2002) and KC (Chapuis et Aubertin, 2003) models, which predict k_{sat} values around 1.0 cm/s and 0.75 cm/s (for n ~ 0.30), respectively.

Figure 5 shows the measured saturated hydraulic conductivity and flow velocity as a function of the hydraulic gradient for waste rock (0-50 mm fraction). It is seen that the flow velocity v (cm/s) increased with the hydraulic gradient. Movement of fine particles was observed at the outlet for measured $i_{cr} \geq 0.11$ and $v_{cr} \geq 0.16$ cm/s. The relationship between the velocity and the hydraulic gradient is not linear for $i \leq 0.44$; more particles suspension was observed in the outlet water for higher gradients. The hydraulic conductivity decreased from 1.2 to 0.8 cm/s, when the hydraulic gradient exceeded the critical value (measured $i_{cr} = 0.11$).

The material was divided into 12 sublayers during column dismantling and the grain size distribution of each layer was analyzed. Figure 6 shows the particle size curves obtained from 12 sublayers (numbered from 1 at the top to

12 at the bottom). Fine particles tended to migrate from the top to the bottom of the column (with the downward water flow). For example, fine particles fraction D ≤ 0.2 mm showed 4.6% of passing in the initial particle size distribution. After the hydraulic loading, the final value varied from 5.3 to 7% for the lower layers.

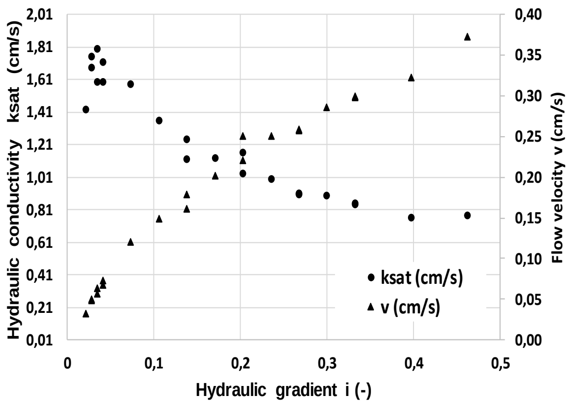

Figure 5. Variations of waste rock (0-50 mm) saturated hydraulic conductivity and flow velocity with respect to the measured hydraulic gradient in the column test

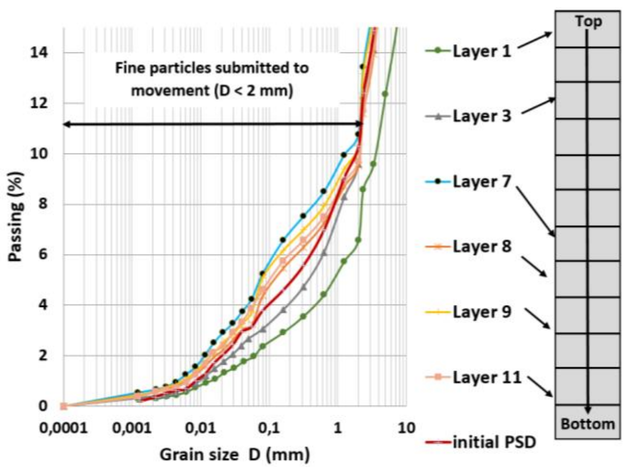

Figure 6. Grain size distribution for the finer fraction (D < 10 mm) of waste rock after column dismantling

These results, which were compared with the initial grain size distribution, indicate that the finer fraction (particle diameter D < 2 mm) was the most susceptible to move in the waste rock 0-50 mm fraction. The maximum diameter of the mobile fraction is larger than the one observed by Peregoedova (2012) (2 mm here, vs 0.4 mm in Peregoedova, 2012). The graphical methods of Kezdi (1969), Sherard (1979) and Kenney and Lau (1985), adapted by Chapuis (1992), indicate that the most mobile fraction has a diameter smaller than 1.8 mm as shown in Figure 7; this value is close to what was observed with the tests presented here. It is recalled that for the methods of Kezdi (1969) and Sherard (1979), the red and blue dashed lines intercept the particle size curve (0-50 mm) at a point (D <1.8 mm), where the slope is lower than 24.9 and 21.5%, respectively. For the method of Kenney and Lau (1985), the slope of the mobile fraction (D <1.8 mm), S, of the grain size curve is less than 33.2 % for the fraction of particles corresponding to F = 20%.

4.2. Movement of tailings though waste rock

Tests 1 and 2 were conducted with sequential deposition of slurry tailings (P= 66%) on the saturated waste rock (0-50 mm fraction) in the instrumented column. These tests showed that tailings initially penetrated the total thickness of saturated waste rock layer. Hydraulic loading was progressively increased after deposition up to critical conditions initiating particles movement. Figure 8 shows flow velocity, v (cm/s) and hydraulic gradients, i (-) for Tests 1 and 2 after tailings deposition. The flow velocity increased with the gradient; tailings movement was observed at critical gradients of 0.13 (Test 1) and 0.14 (Test 2). Velocities around the critical gradient were comprised between 0.18 cm/s (Test 1) and 0.26 cm/s (Test 2). The gradual increase in the hydraulic gradient to a maximum value of 0.44 produced a nonlinear flow velocity behaviour.

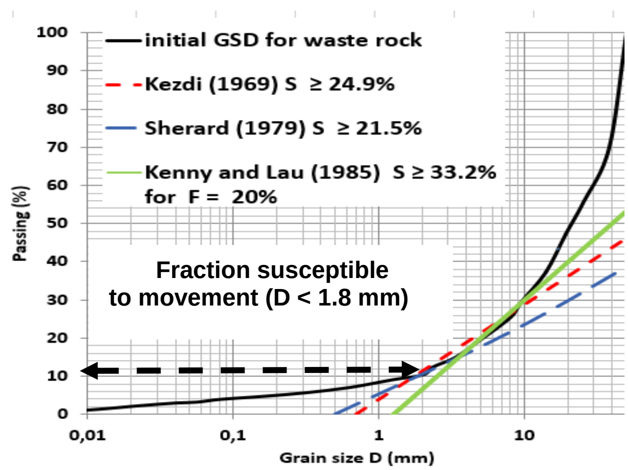

Figure 7. Filter criteria for waste rock using the graphical methods proposed by Kezdi (1969), Sherard (1979), Kenny and Lau (1985), and adapted by Chapuis (1992); see details in the text.

Figure 9 presents the waste rock hydraulic conductivity measured for increasing gradients after tailings deposition. The initial values of k_{sat} (0-50 mm) under low gradient (i = 0.02 - 0.03) were comprised between 1.4 and 1.8 cm/s. The values of k_{sat} shortly after tailings deposition were comprised between 1.5 and 2 cm/s for both Tests 1 and 2. Tailings movements were not observed for low gradients i < 0.03. For Test 1, the saturated hydraulic conductivity decreased from 2.1 to 1.3 cm/s, when the gradient increased from 0.023 to 0.13 (close to its critical value) and to 0.6 cm/s when i reached 0.44. For Test 2, k_{sat} values varied from 1.5 to 2.0 cm/s, when the hydraulic gradient increased from 0.03 to 0.06, and tended to decrease down to 1.7 cm/s when the critical gradient (measured) i_c = 0.14

was reached. The k_{sat} value continued to decrease down to 0.6 cm/s for increasing gradients ($i \leq 0.44$).

Waste rock grain size distribution was also determined after the end of the test (i.e. after the maximum hydraulic gradient was reached). The fine particles fraction D < 2 mm was identified as being susceptible to movement according to grain size analyses results, obtained from the internal movement of waste rock 0-50 mm (Figure 6).

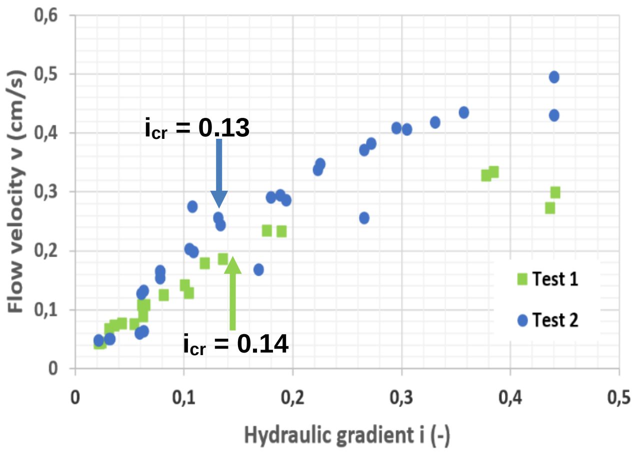

Figure 8. Flow velocity after tailings deposition with increasing hydraulic gradients for Tests 1 and 2, conducted in an instrumented column containing waste rock (0-50 mm)

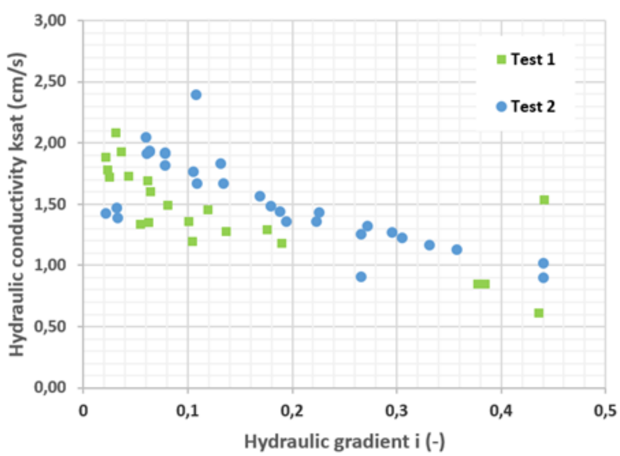

Figure 9. Hydraulic conductivity measured in the instrumented columns containing waste rock (0-50 mm) and tailings for an increasing hydraulic gradient (Tests 1 and 2)

Figure 10 shows the distribution of fine (mobile) particles with D < 2 mm, along the entire height of waste rock divided in 13 and 10 layers (from top to bottom) of 6 cm (thickness) for Tests 1 and 2, respectively. The initial percentage of the fines fraction (D < 2 mm) was 10% in the waste rock layers for both tests. For Test 1, the fines particles percentage was higher than the initial value, ranging from 12 to 16.6% along the height of waste rock layers. For Test 2, the percentage of fines was between 13 and 16.5%. The bottom layers of the column for Test 2 showed a 2 to 4% lower fine percentage compared to the initial value, after tailings deposition and hydraulic loading.

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Sequence deposition of slurry tailings (P = 66%) in contact with saturated waste rock (Tests 1 and 2) followed by a hydraulic loading, showed that tailings could flow through waste rock pores with a slight retention of tailings (between 2 and 6.5%).

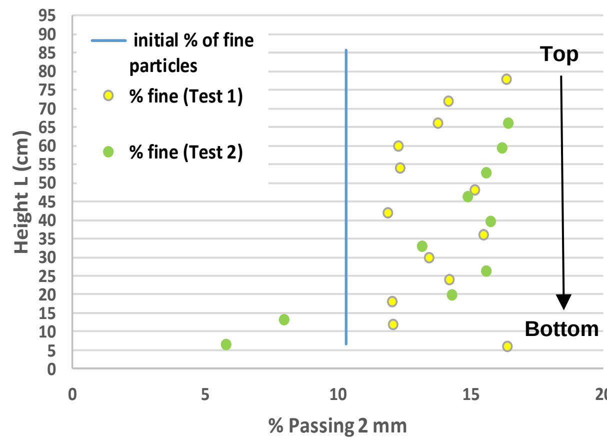

Figure 10. Distribution of fine (mobile) particles over the entire height of the waste rock (sublayers) for Tests 1 and 2

5. DISCUSSION AND FINAL REMARKS

This experimental study aimed at evaluating migration of fine waste rock particles and tailings through waste rock pores, and the effect on the saturated hydraulic conductivity and drainage capacity of WRI systems.

Permeability tests were conducted on a well-graded waste rock (0-50 mm) with increasing hydraulic loading steps and a downward flow in an instrumented column., The tests results indicate that a critical condition occurred for an hydraulic gradient i_{cr} = 0.11 and at velocity v = 0.16 cm/s. The hydraulic conductivity tends to decrease with an increasing gradient above I_{cr}, due to the fine particles movement through pores and their accumulation in the lower sections of the waste rock column. Fine particles D < 2 mm are prone to movement under these critical conditions. Coarser grains don't move, but they support a primary fabric and the transfer of effective stress (Skempton and Brogan, 1994; Chapuis 2016). The graphical methods of Kezdi (1969), Sherard (1979), Kenney and Lau (1985), adapted by Chapuis (1992), indicate that the most mobile fraction is less than about 1.8 mm, which is so close to the observed fraction in this experimental study (D < 2 mm). This suggests that these graphical methods can also be applied to a waste rock with D ≤ 50 mm, to identify the moving fraction. Very large hydraulic gradients were not tested in this study.

The movement of tailings through the pores of waste rock (0-50 mm) was assessed by conducting two specific tests in an instrumented column. For Tests 1 and 2, the critical gradient values were 0.13 and 0.14, respectively. The measured hydraulic conductivity showed a slight variation under low gradient, and it was reduced by a factor of 2 when the gradient was increased to its critical value. For saturated waste rock 0-50 mm, clogging mechanisms appear to be less pronounced when sequential deposition of a denser slurry of tailings (P = 66%) was applied, with a free passage of the tailings and low retention of fines.

Further work is currently underway to assess the effects of unsaturated conditions, flow direction, coarser and finer grain sizes, macroporosity and density on particles migration. Assessing these parameters can help understand better the in-situ hydrogeotechnical behaviour of WRI in tailings impoundments.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Adel, H.D., Bakker, K.J., Breteler, M.K. (1988). Internal stability of minestone. *Proceedings of the International Symposium on Modelling Soil Water-Structure Interactions* Balkema, pp. 225-231 Rotterdam.

Alhaddad, S., Alem, A., Wang, H., Benamar, A. & Ahfir, N. (2008). Effet des conditions hydrauliques et de la forme des grains sur l'érosion interne dans un milieu poreux. XXVIémes Rencontres Universitaires de Génie Civil. Nancy, France, p. 1-8.

ASTM. (2001). Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter, USA /D5084-00.

ASTM. (2002). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. USA/ D 854-02.

ASTM (2006). Standard Test Method for Permeability of Granular Soils (Constant Head) (D2434), ASTM International, West Conshohocken, PA.

ASTM (2010). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D854), ASTM International, West Conshohocken, PA.

ASTM (2015). Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate (C127), ASTM International, West Conshohocken, PA.

ASTM (2017). Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis (D7928), ASTM International, West Conshohocken, PA.

ASTM (2017). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (D2487), ASTM International, West Conshohocken, PA.

Aubertin, M., Bussière, B., and Chapuis, R. P. (1996). Hydraulic Conductivity of Homogenized Tailings From Hard Rock Mines. *Canadian Geotechnical Journal*, 33(3) : 470-482.

Aubertin, M., Bussière, B., & Bernier, L. (2002a). Environnement et Gestion des Rejets Miniers. Manual on CD-Rom, Presses internationales Polytechnique

Aubertin, M., Mbonimpa, M., Jolette, D., Bussière, B., Chapuis, R. P., James, M., & Riffon, O. (2002b). Stabilité géotechnique des ouvrages de retenue pour les résidus miniers : Problème Persistants et méthodes de contrôle [CD-ROM]. In Symposium 2002 on Mining and the Environment : Challenges and Pro-spects, Rouyn-Noranda, Que., 3-5 November 2002. Canadian Institute of Mining, Metallurgy, and Petroleum, papers32a1019p.526.

Benamar, A., Wang, H., Ahfir, N., Alem, A., Massei, N. & Dupont, J.-P. (2005). Effets de la vitesse d'écoulement sur le transport et la cinétique de dépôt de particules en suspension en milieu poreux saturé. C. R. Geoscience, 337, 497-504.

L.Bolduc, F. (2012). Une étude sur l'utilisation des roches stériles comme inclusions drainantes dans les résidus miniers. Mémoire de maîtrise, École Polytechnique de Montreal, Québec, Canada.

L.Bolduc, F., and Aubertin, M. 2014. Numerical investigation of the influence of waste rock inclusions on tailings consolidation. Canadian Geotechnical Journal, 51(9): 1021–1032. doi:10.1139/cgj-2013-0137.

Boudrias, G. (2018). Évaluation numérique et expérimentale du drainage et de la consolidation de résidus miniers à proximité d'une inclusion de roches stériles Mémoire de maîtrise, École Polytechnique de Montréal, Québec, Canada.

Bussière, B. (2007). Hydro-geotechnical properties of hard rock tailings from metal mines and emerging geo-environmental disposal approaches. Canadian Geotechnical Journal, 44 1019-1052.

Bussière, B., Demers, I., Dawood, I., Plante, B., Aubertin, M., Peregoedova, A., Pepin, G., Lessard, G., Intissar, R., Benzaazoua, M., Molson, J., Chouteau, M., Zagury, G., Monzon, M. & Laflamme, D. (2011). comportement géochimique et hydrogéologique des stériles de la mine Lac Tio. Comptes-rendus du Symposium 2011 sur l'Environnement et les Mines. Rouyn-Noranda, Québec, Canada, CD-ROM.

Chapuis, R. P. (1992). Similarity of internal stability criteria for granular soils. Canadian Geotechnical Journal, 29, 711-713.

Chapuis, R. P. & Aubertin, M. (2003). On the use of the Kozeny-Carman equation to predict the hydraulic conductivity of soils. Canadian Geotechnical Journal, 40, 616-628.

Chapuis, R.P. 2004. Permeability tests in rigid-wall permeameters: Determining the degree of saturation, its evolution and influence on test results. Geotechnical Testing Journal, 27(3): 304–313.

Chapuis, R. P., Masse, I., Madinier, B. & Aubertin, M. (2007). A drainage column test for determining unsaturated properties of coarse materials. Geotechnical testing journal, 30(2), 83-89.

Chapuis, R.P. 2009. Relating hydraulic gradient, quicksand, bottom heave, and internal erosion of fine particles. Geotechnical News, 27(4): 36–38.

Chapuis, R.P. 2016. Testing for internal erosion and evaluating quantitatively the observable facts. Proceedings of the 69th Canadian Geotechnical Conference. Vancouver, Canada, 8 p.

Ferdosi B, James M, Aubertin M. (2015). Investigation of the effect of waste rock inclusions configuration on the seismic performance of a tailings impoundment. Geotechnical and Geological Engineering. 33(6):1519–1537.

Gamache-Rochette, A. (2004). Une étude de caractérisation en laboratoire et sur le terrain des écoulements de l'eau dans les roches stériles. Mémoire de maîtrise. École Polytechnique de Montréal, Québec, Canada.

Holtz, R.D., & Kovacs, W.E. (1991). *Introduction à la géotechnique* (traduit par J. Lafleur). Presses Internationales Polytechnique, Montréal.

James, M. 2009. The use of waste rock inclusions to control the effect of liquefaction in tailings impoundments. Thèse de doctorat. École Polytechnique de Montréal, Québec, Canada.

James, M., et Aubertin, M. (2010). On the dynamic response of tailings and stability of tailings impoundments for hard rock mines, Geotechnical News, Sept. 2010, 39-43.

James, M., Aubertin, M., Bussiére, B. (2013). On the use of waste rock inclusions to improve the performance of tailings impoundments. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, pp. 735–738

Jaouhar, E. (2012). Analyse de l'effet d'inclusions drainantes sur la consolidation de sols fins et de résidus miniers. Mémoire de maîtrise, École Polytechnique de Montréal, Québec, Canada.

James, M., Aubertin, M., Bussière, B., Pednault, C., Pépin, N., et Limoges, M. (2017). A research project on the use of waste rock inclusions to improve the performance of tailings impoundments. Proceedings of the 69th Canadian Geotechnical Conference. GeoOttawa, Canada. 8 p.

Kenney, T.C., and Lau, D. 1985. Internal stability of granular filters. Canadian Geotechnical Journal, 22: 215-225.

Kezdi, A. 1969. Increase of protective capacity of flood control dikes (in Hungarian). Department of Geotechnique, Technical University, Budapest, Report Nº.1.

Massei, N., Lacroix, M., Wang, H. Q. & Dupont, J.-P. (2002). Transport of particulate material and dissolved tracer in a highly permeable porous medium: comparison of the transfer parameters. Journal of Contaminant Hydrology, 57, 21-39.

Mbonimpa, M., Aubertin, M., Chapuis, R.P., & Bussière, B. (2002). Practical pedotransfer functions for estimating the saturated hydraulic conductivity. Geotechnical and Geological Engineering, 20, 235-259.

McLemore, V. T., Fakhimi, A., Zyl, D. V., Ayakwah, G. F., Anim, K., Boakye, K., Ennin, F., Felli, P., Fredlund, D., Gutierrez. L. A. F., Nunoo, S., Tachie-Menson, S., et Viterbo, V. C. (2009). Literature Review of other rock piles: characterization, weathering, and Stability, Questa Rock Pile Weathering Stability Project. 101pages.http://geoinfo.nmt.edu/staff/mclemore/documents/ofr_517.pdf.

Morin, K. A., Gerencher, E., Jones, C. E. & Konasewich, D. E. (1991). Critical literature review of acid drainage from waste rock. Canadian Mine Environmental Neutral Drainage (MEND) Program. Canada Centre for Mineral and Energy Technology.

Pépin, N. (2010). Étude du comportement cyclique de résidus miniers avec inclusions drainantes par essais sur table sismique. Mémoire de maîtrise, École Polytechnique de Montréal, Québec, Canada.

Pépin, N.P. (2012). Èlaboration et implémentation d'un protocole de laboratoire pour l'étude du potentiel de liquéfaction de résidus miniers. Mémoire de maîtrise, École Polytechnique de Montréal, Québec, Canada.

Peregoedoa, A., Aubertin, M. & Bussière, B. (2013). Laboratory measurement and prediction of the saturated hydraulic conductivity of mine waste rock. 66th Canadian Geotechnical Conference, Montréal, Canada, 6 p.

Peregoedova, A. (2012). Étude expérimentale des propriétés hydrogéologiques de stériles miniers. Mémoire de maîtrise, École Polytechnique de Montréal, Québec, Canada.

Reddi, L., Ming, X., Hajra, M., and Lee, I. (2000). "Permeability Reduction of Soil Filters due to Physical Clogging." ASCE J. Geotech. Geoenviron. Eng., 126:3: 236-246.

Rey, N., Demers, I., Bussière. (2014). Experimental study of tailings percolation into waste rock. Proceedings of the 67th Canadian Geotechnical Conference. Georegina, P218.

Riffon,O. (2005). Étude en laboratoire sur la migration des particules fines lors d'essais de perméabilité sur des sables et des silts. Mémoire de maitrise. École Polytechnique de Montréal, Québec, Canada.

Saleh Mbemba, F. (2016). Évaluation du drainage, de la consolidation et de la dessiccation des résidus miniers en présence d'inclusions de roches stériles. Thèse de doctorat. École Polytechnique de Montréal, Québec, Canada.

Sherard, J.L., and Dunnigan, L.P. 1986. Internal stability of granular filters: Discussion. Canadian Geotechnical Journal, 23(3): 418–420.

Skempton, A.W., and Brogan, J.M. 1994. Experiments on piping in sandy gravels. Géotechnique, 44(3): 449–460.

Terzaghi, K. 1943. Theoretical soil mechanics. John Wiley & Sons, New York.