An assessment of hydrogeological properties of waste rock using infiltration tests and numerical simulations

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ABSTRACT

Waste rocks are excavated to access the mine orebody and usually disposed of in piles at the surface. The grain size of waste rock from hard rock mines can vary from silt sized particles to large boulders (≥ 1 m). Characterization of their hydrogeological properties is challenging because of their grain size distribution and natural heterogeneity. The flow of water in waste rock piles is mainly controlled by the sandy and gravelly fractions, but the presence of larger particles can create macropores that may influence the hydrogeological characteristics.

In this article, the experimental results from a series of infiltration tests conducted on a waste rock pile are analyzed using numerical simulations to assess the local hydrogeological properties of the waste rock from back analyses. The relative influence of the grain size, porosity and water retention capacity on infiltration rates was also evaluated. The article illustrates how this methodology can be used to obtain in-situ hydrogeological properties of waste rock.

RÉSUMÉ

Les roches stériles sont excavées pour accéder au gisement de la mine, et elles sont usuellement déposées dans des haldes à la surface. Les particules de stériles ont une dimension qui varie de la taille d'un silt à celle de gros blocs (≥ 1 m). Cette granulométrie très étalée combinée à l'hétérogénéité de ces matériaux rend la caractérisation de leurs propriétés hydrogéologiques complexe. L'écoulement de l'eau dans les haldes à stériles est habituellement contrôlé par les fractions sable et gravier, mais la présence de particules plus grossières et plus fines peut créer des macropores qui influencent les caractéristiques hydrogéologiques.

Dans cet article, les résultats expérimentaux d'une série d'essais d'infiltration effectués à la surface d'une halde à stériles sont présentés et analysés à l'aide de simulations numériques afin d'évaluer les propriétés hydrogéologiques locales par analyses inverses. L'importance relative de la courbe granulométrique, de la porosité et de la capacité de rétention d'eau des stériles sur les taux d'infiltration sont évaluées. L'article illustre comment cette méthodologie peut être utilisée pour obtenir les propriétés hydrogéologiques des roches stériles en place.

1 INTRODUCTION

Waste rocks contain little or no minerals of economic value. They are removed by blasting to access the orebody during the mining cycle. Mine waste rocks are typically placed on the surface in piles. The waste rock produced in hard rock mines are widely graded with particles ranging from sand and silt to boulders having a diameter of 1 m or more (Piteau 1991; Hustrulid et al. 2000; Aubertin et al. 2002; McLemore et al. 2009; Hawley and Cunning 2017).

A waste rock pile may become problematic when it contains reactive minerals, such as iron sulphides, that can produce contaminated mine drainage, CMD (either neutral or acidic). Large piles may also raise concerns regarding their geotechnical stability (Piteau 1991; Hustrulid et al. 2000; Aubertin et al. 2002, 2013).

A few approaches are being used or considered to minimize the risks and environmental impact of waste rock piles (e.g. Li et al. 2014, Hawley and Cunning 2017). One of these techniques consists of reducing water infiltration into the potentially reactive waste rock by adding inclined layers of compacted material (Aubertin et al. 2002, 2005, 2013; Fala et al. 2003, 2005, 2013; Martin et al. 2005, 2017, 2019). The application of such a technique requires the analysis of water flow into an unsaturated waste rock pile. It is however challenging to evaluate waste rock hydrogeotechnical properties (in the laboratory or in the field), in part because the presence of large cobbles and boulders affect the sampling and testing, while also producing natural heterogeneity in the material.

A practical and useful option that helps to circumvent some of the difficulties associated with waste rock characteristics is to conduct relatively large-scale infiltration tests in the field (Martin 2003; Gamache-Rochette 2004; Fala 2008; Lessard 2011). Such in-situ tests can account for the main features including the material heterogeneity and presence of large particles

Infiltration tests in the field have long been used to evaluate the field (satiated) hydraulic conductivity (k_{fs}), which is typically somewhat smaller than the saturated hydraulic conductivity (k_{sat}). In practice, the former (k_{fs}) may correspond to about half of k_{sat} for sandy soils and a quarter of k_{sat} for clays and silts (Bouwer 2002).

The interpretation of infiltration tests can however be challenging. It is often based on simplified infiltration models such as those of Green and Ampt (1911) and Philipp (1957a, 1957b, 1957c, 1957d, 1957e, 1958). These models require parameters that may be difficult to characterize (particularly in waste rock) such as the depth of the wetting front and the corresponding local pore water pressure (suction).

Numerical simulations can also be used to interpret infiltration tests and to estimate the field hydraulic conductivity (k_{fs}) of waste rock. Such a numerical approach is applied here to interpret tests conducted by Lessard (2011) on the Petit-Pas waste rock pile at the Tio mine (Rio Tinto Fer et Titane, Havre-St-Pierre, Quebec).

2 BACKGROUND INFORMATION

As stated above, the wide range of particle sizes makes it difficult to characterize the hydrogeological (and geotechnical) properties of waste rock. In this regard, a few experimental methods based on commonly used tests have been adapted both in the laboratory (e.g. Hernandez 2007; Peregoedova 2012; Peregoedova et al. 2013, 2014) and in the field (e.g. Zhan et al. 2001a, 2001b; Aubertin et al. 2002, 2005; Gamache-Rochette 2004, Fala 2008).

For instance, Peregoedova et al. (2013) conducted permeability test to evaluate the saturated hydraulic conductivity (k_{sat}) of the Tio mine (ilmenite) waste rock in large size rigid wall permeameters, using a procedure adapted by a standard method (ASTM D5856). The instrumented column used for these tests had a height of about 1 m and a diameter of 0.3 m. The saturated hydraulic conductivity (k_{sat}) tests were completed on specimens with various grain sizes; the maximum particle sizes ranged from 5 mm to 50 mm. The porosity (n) of the specimens varied between 0.2 and 0.3 (void radio, e, between 0.25 and 0.4)

The measured saturated hydraulic conductivity (k_{sat}) of the Tio mine waste rock varied between 1×10^{-4} m/s and 1×10^{-3} m/s for the fractions tested. The value of the saturated hydraulic conductivity (k_{sat}) was not influenced significantly by the amount of coarse grains (gravel) in the specimens. It appeared mainly to be controlled by the flow in the macropores (Peregoedova et al. 2013).

The same instrumented columns were also used to assess the water retention curve under drainage conditions. The suction in the columns was controlled by placing a fixed water table (ψ = 0 kPa) at the base using a U-tube. The porosity and volumetric water content were measured for each layer of waste rock at different elevations upon dismantling (Peregoedova et al. 2014; see also Hernandez 2007 and Peregoedova 2012).

The experimental results indicated that the air entry value AEV (determined on the water retention curve) was below 10 cm. The AEV was not significantly influenced by the maximum grain size of the waste rock (Peregoedova et al. 2014). However, the residual water content (θ_r), which is between 0.02 and 0.08, was affected by the percentage of fine particles in the material.

Similar waste rock properties were also evaluated in the field using infiltration tests. The procedures for such in-situ tests are described by Zhan et al. (2001a, 2001b), Martin (2003), Gamache-Rochette (2004), Fala (2008), Lessard (2011), Bréard Lanoix et al. (2017), Dubuc et al. (2017), and Dubuc (2018). One of the objectives of these tests was to assess in-situ properties of the waste rocks under natural conditions, considering the typical variations in their characteristics. Among these experimental investigations, the experimental results from Lessard (2011), who conducted infiltration tests on the waste rock piles of the Tio mine, are presented and analysed in the following.

3 IN-SITU TESTS

3.1 EXPERIMENTAL PROCEDURES

Two types of infiltration tests were conducted on the waste rock pile (Lessard 2011). The first was constant head tests in single ring infiltrometers (i.e. 20-liter buckets with large holes in the bottom) (Figure 1). The second type consisted of constant head tests in ponds constructed at the surface of the waste rock pile (Figure 2 and Figure 3). The radius of the infiltration surface was 0.15 m for the buckets and between 0.4 m and 0.7 m for the ponds. The zone below some of the infiltration ponds was instrumented with VWC and suction probes (Figure 2), but these instruments did not provide reliable data (results not used here). More information on these measurements is presented by Lessard (2011).

After water filling of the infiltrometer or pond, a (relatively) constant hydraulic head (between 1 cm and 10 cm, depending on the test) was maintained during the infiltration tests by adjusting the flow rate from 1 m^3 reservoirs (tote-tanks) using a ball valve. The hydraulic head, height of water in the reservoirs, and volume of infiltrated water were recorded at regular intervals. The rate of water infiltration was then calculated.

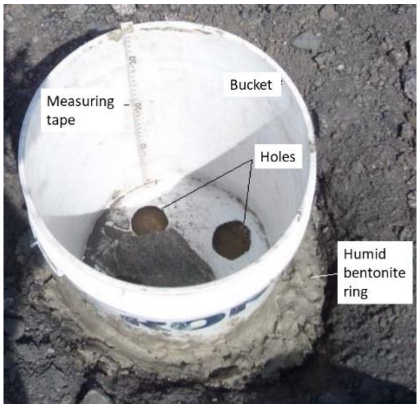

Figure 1. Photo of one of the infiltrometers (buckets) used for the small-scale infiltration tests (Lessard 2011).

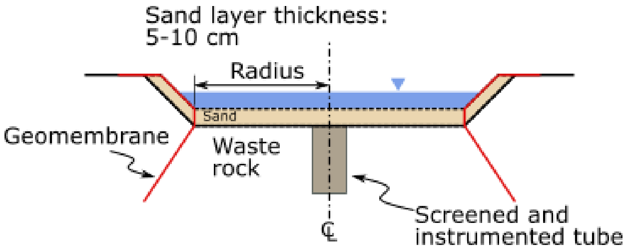

Figure 2. Cross-section of the infiltration ponds used for the large-size infiltration tests (*Not to scale,* adapted from Lessard 2011).

Figure 3. Photo of one of the infiltration ponds used for the infiltration tests (Lessard 2011).

3.2 MAIN RESULTS

A total of 11 infiltration tests were completed by Lessard (2011), i.e. 5 in buckets (B1 to B6) and 6 in constructed ponds (P1 to P7). The total normalized infiltration volume per unit area (V/A – m^3/m^2) with respect to time is presented in Figure 4 (buckets) and Figure 5 (ponds) for all the tests. The results tend to follow a quasi-linear trend; the average measured rates obtained for each in-situ test is presented in Table 1.

The slope of the relationships shown in these figures gives the infiltration (flow) rate (q, m/s). The minimum and maximum infiltration rates for the in-situ infiltration tests in the small infiltration tests (buckets) are 7.0×10^{-5} m/s and 1.2×10^{-3} m/s, respectively; the infiltration rate (q) was between 1.1×10^{-4} m/s and 4.7×10^{-4} m/s for the infiltration test in ponds. Variability of the infiltration rate was much higher for the smaller scale tests (in the buckets). The variations may be due to the different grain sizes and densities at different locations. The results obtained for the tests in ponds appear to be within the expected margin of error for such type of tests and materials.

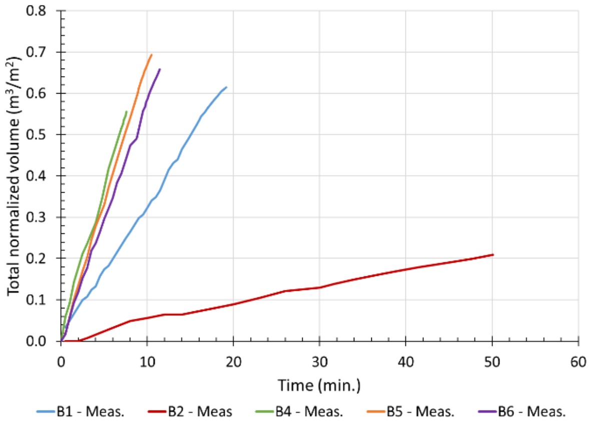

Figure 4. Normalized volume (V/A) with respect to time (measured) for the infiltration tests conducted in single ring infiltrometers (buckets) (Lessard 2011).

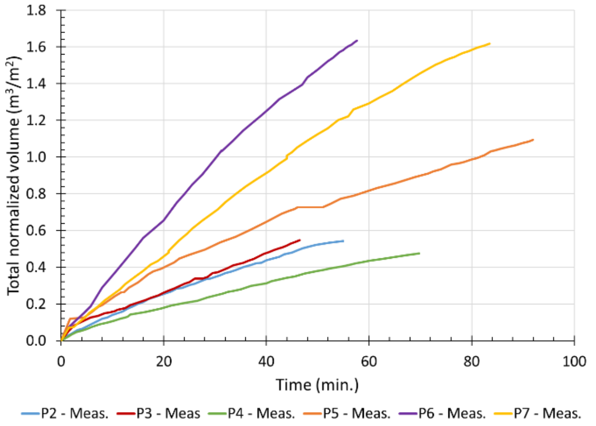

Figure 5. Normalized volume (V/A) with respect to time (measured) for the infiltration tests conducted in constructed ponds (Lessard 2011).

Table 1. Measured (average) infiltration rates (q, m/s) obtained from the tests completed by Lessard (2011).

Buckets		Pond	
B1	5.3×10^{-4}	P2	1.6×10^{-4}
B2	7.0×10^{-5}	P3	2.0×10^{-4}
B4	1.2×10^{-3}	P4	1.1×10^{-4}
B5	1.1×10^{-3}	P5	2.0×10^{-4}
B6	9.6×10^{-4}	P6	4.7×10^{-4}
		P7	3.2×10^{-4}

(2

4 NUMERICAL SIMULATIONS

The software used for numerically simulating the infiltration tests is SEEP/W (GeoStudio, 2018). This finite element software uses the Richards (1931) equation to model flow in porous media. It has been used in the past to simulate water flow in coarse grained materials including waste rocks (e.g. Martin 2003; Martin et al. 2005; Bréard Lanoix et al. 2017; Dubuc 2018). The required assessment has been conducted with the code before conducting the simulations presented here (Chapuis et al. 2001).

The numerical simulations of the infiltration tests are based on an axisymmetric model (Figure 6). This model consists of triangular and rectangular elements. The elements are smaller (2 cm) close to the infiltration zone, and larger (up to 40 cm) near the outer limits. The boundary condition was a unit hydraulic gradient (i = 1). The infiltration boundary condition at the surface was the measured hydraulic heads by Lessard (2011). The size of the infiltration zone corresponds to the radius of the test being simulated (i.e. 0.15 m for buckets and between 0.4 m and 0.7 m for the ponds). The initial volumetric water content at the surface of the waste rock was set at the value corresponding to the residual suction of the water retention curve, WRC ($\psi_r \approx 50$ kPa, see below), which gives a residual volumetric water content of the material ($\theta_r = 0.04$). The water balance error was below 1% for these simulations. Although dominated by vertical flow below the infiltration surface, the models simulated 2D flow, with some water moving laterally (radially) during (and after) the tests.

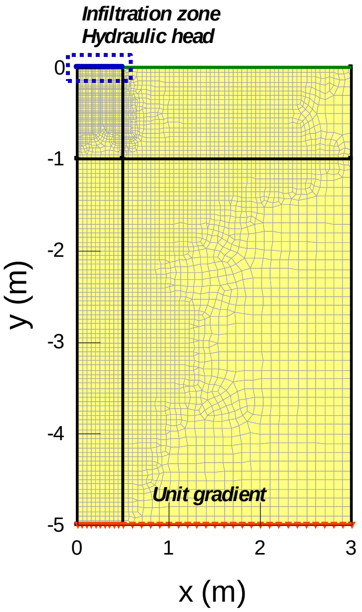

Figure 6. Axisymmetric model to simulate water flow below the circular infiltration surface (all other external boundaries are considered no flow).

One of the main objectives of the numerical simulations was to reproduce the in-situ infiltration tests results, based on the infiltration rate (q) and cumulative normalized infiltrated volume (V/A).

The water retention curve (WRC) of the waste rock (for the base case) was adapted from the laboratory measurements presented by Peregoedova et al. (2014), with adjustments (calibration) for field conditions made by Dubuc (2018) (Figure 7).

The Fredlund and Xing (1994) model was used to represent the WRC; the corresponding parameters are (for the base case): $a_{fx} = 1$ kPa; $n_{fx} = 1.9$; $m_{fx} = 0.9$, for a saturated volumetric water content (θ_s) of 0.25. It is equal to the porosity of the waste rock (n), based on the average values measured by the Authors at the surface of the Petit-Pas waste rock pile (Tio mine) using a nuclear density probe (Troxler 3440) in 2017; this value of the porosity is similar to values measured by Peregoedova et al. (2014) in the laboratory on columns composed of waste rock from the Tio mine. The air entry value (ψ_a or AEV) and residual suction (ψ_r) are about 0.5 kPa and 50 kPa, respectively.

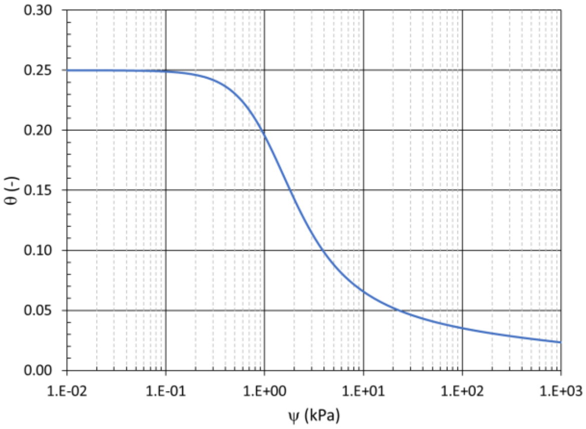

Figure 7. Water retention curve obtained with the Fredlund and Xing (1994) model (base case) of the waste rock in the simulations (adapted from Peregoedova 2012 and Dubuc 2018).

The field hydraulic conductivity of the waste rock was evaluated by varying the saturated hydraulic conductivity (k_{sat}) in the model between 1×10^{-5} m/s and 1×10^{-3} m/s (using also the WRC shown in Figure 87 for the base case). This range of hydraulic conductivity corresponds to the variation of the saturated hydraulic conductivity for waste rock observed by Peregoedova et al. (2013). It was then possible to estimate the field hydraulic conductivity from back calculations, using numerical simulations, based on the infiltration tests results,

The corresponding unsaturated hydraulic conductivity function (range) shown in Figure 8 was estimated using the Fredlund et al. (1994) equation, which is integrated in the GeoStudio package (GeoSlope International, 2018).

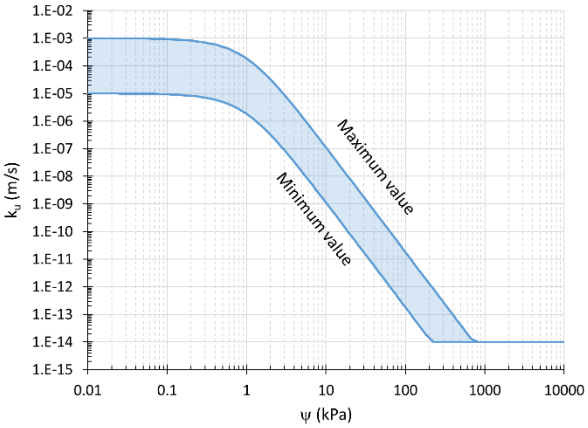

Figure 8. Range of the unsaturated hydraulic conductivity function for the waste rock used in the numerical simulations (based on the Fredlund et al. 1994 model).

The total infiltrated normalized volume (V/A) of water obtained from the numerical simulations was first compared with the normalized volume (V/A) measured during the in-situ tests. It was then possible to estimate the field (satiated) hydraulic conductivity (k_{fs}). For example, Figure 9 shows the total (normalized) volume calculated for different values of the saturated hydraulic conductivity of the waste rock for the simulation of infiltration test P4. It is seen that there was a linear relationship between the simulated total infiltrated volume and the saturated hydraulic conductivity (k_{sat}) of the waste rocks. The field hydraulic conductivity (k_{fs}) for this infiltration test is then given by the hydraulic conductivity that corresponds to the normalized volume measured in the field (0.5 m^3/m^2), or 9×10^{-5} m/s (red square on Figure 9).

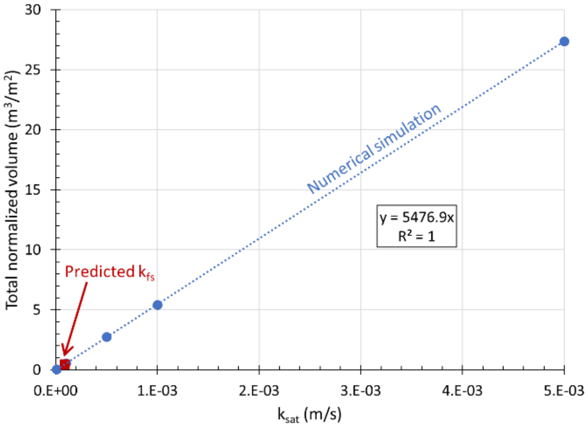

Figure 9. Simulated total normalized infiltration volume for different values of the hydraulic conductivity in the simulation of Test P-4

The infiltration rate (q) simulated with the interpolated hydraulic conductivity (obtained with the method described above) was then compared with the actual field infiltration measurements. Figure 10 presents an example for infiltration Test P4. The hydraulic head (h) above the simulated infiltration surface corresponded to the value measured in the field. As seen in Figure 10, the in-situ infiltration rate was variable because of the variations in the hydraulic head during the test. Nonetheless, there is generally a good agreement between the measured and simulated infiltration rates when using the adjusted (interpolated) hydraulic conductivity values.

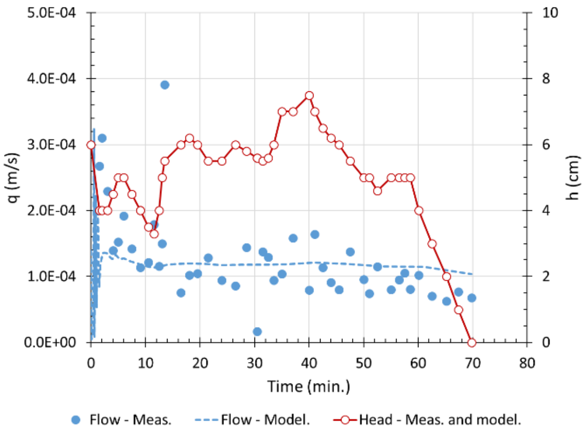

Figure 10. Example of the simulated flow rates compared to the measured flow rates during the infiltration test P4 (the hydraulic head measured in the field, and applied to the numerical simulation, is also shown).

The methodology and the simulation results described above were used to assess the field hydraulic conductivity (k_{fs}) from the 11 in-situ infiltration tests performed by Lessard (2011) at the surface of the waste rock pile. There is a good agreement between the simulated and measured normalized volumes (V/A) (Figure 11). The field hydraulic conductivity (k_{fs}) varied between 2×10^{-5} m/s and 4×10^{-4} m/s for the tests completed in the buckets, and from 9×10^{-5} m/s and 3×10^{-4} m/s for the tests completed in the constructed ponds.

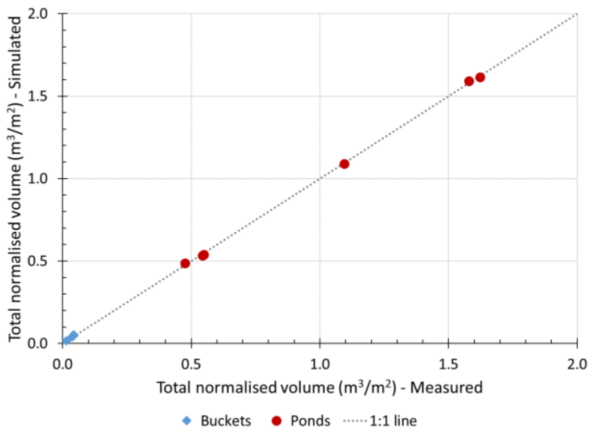

Figure 11. Comparison between the simulated and measured total normalized infiltration volume (V/A) for the 11 infiltration tests completed by Lessard (2011).

5 SENSITIVITY ANALYSES

Unknown parameters may influence the results of the numerical simulations that were conducted. For instance, the initial water content at the beginning of the in-situ infiltration tests was not known precisely. It was estimated that the surface of the waste rock was at the average residual value, i.e. $\theta_r = 0.04$. Using the Test P4 as an example, it is shown that varying the initial water content between 0.04 (residual) and 0.25 (saturated) had little effect on the field hydraulic conductivity (k_{fs}, Figure 12). However, the value of the field hydraulic conductivity (k_{fs}) determined by the numerical simulations increased when the initial VWC of the waste rock was set below the residual water content (Figure 12).

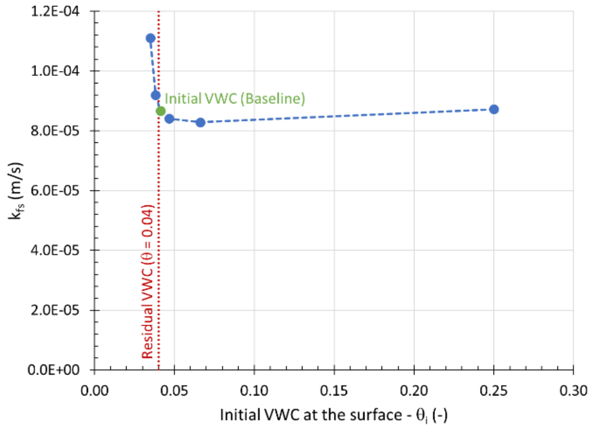

Figure 12. Effect of the initial volumetric water content (θ) at the surface of the waste rock at the beginning of the infiltration test on the field hydraulic conductivity (k_{fs}) simulated for Test P4

The effect of the shape of WRC was also assessed. The parameter a_{fx} of the Fredlund and Xing (1994) model was varied, to consider the influence of the air entry value (AEV) of the material. The parameter a_{fx} was varied between 0.5 kPa (giving an AEV = 0.25 kPa) and 10 kPa (AEV = 5 kPa), which corresponds to the typical range of the WRC for mine waste rocks (Peregoedova 2012; Peregoedova et al. 2013; James et al. 2013).

A smaller value of parameter a_{fx} leads to a higher field hydraulic conductivity: $k_{fs} = 1.1\times10^{-4}$ m/s was obtained for $a_{fx} = 0.5$ kPa compared with $k_{fs} = 4.4\times10^{-5}$ m/s for $a_{fx} = 10$ kPa. The variation in the simulated field hydraulic conductivity (k_{fs}) is within an order of magnitude from the base case (with $a_{fx} = 1$ kPa, AEV = 0.5 kPa). It therefore appears that the WRC has a limited impact on the determination of the field hydraulic conductivity (k_{fs}) using the numerical models (for the conditions considered here).

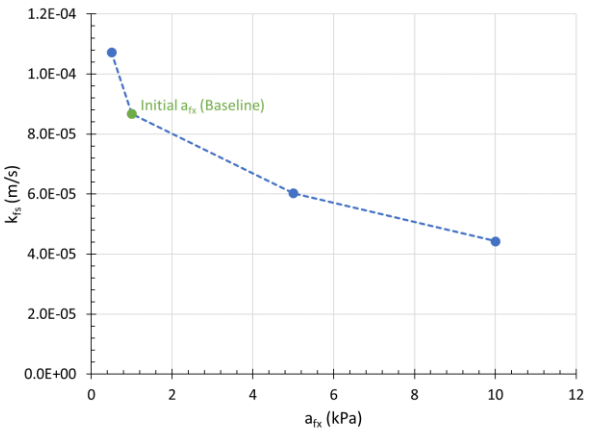

Figure 13. Effect of the water retention curve parameter a_{fx} from the Fredlund and Xing (1994) model on the simulated hydraulic conductivity (k_{fs}) for Test P4.

6 DISCUSSION AND CLOSING REMARKS

The methodology presented above was used to estimate the in-situ hydraulic conductivity of mine waste rocks. With the software SEEP/w (GeoStudio, 2018) and experimental results from Lessard (2011), it was assessed that the average k_{fs} at the surface of the Petit-Pas waste rock pile at the Lac Tio mine was around 1.7×10^{-4} m/s. Lower values were observed in areas with a higher in-situ density (due to trafficking). A similar method was applied by Bréard Lanoix et al. (2017) to estimate the hydrogeological properties of a sand layer placed on an experimental waste rock pile.

The estimation of the field hydraulic conductivity could be improved by evaluating first the initial volumetric water content at the surface of the waste rock.

The simulation results also indicated that the AEV of the waste rock (typically between 0.25 kPa and 5 kPa) had little influence on the value back calculated for the in-situ (satiated) hydraulic conductivity (k_{fs}). The value of the AEV can be evaluated from laboratory tests using the procedure described by Peregoedova et al. (2014).

Ongoing work includes the application of the methodology described above to assess the hydraulic conductivity (k_{fs}) from relatively large size laboratory column tests (Lévesque, 2015) and other large scale field tests results. The sensitivity analysis is also being expanded to address other conditions.

7 ACKNOWLEDGEMENTS

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