A combined hydrogeological–geophysical approach to evaluate unsaturated flow in a large waste rock pile.

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ABSTRACT
Waste rock is generated in a mine so as to access its ore body. This widely graded, coarse-grained material is typically stored in piles on the ground surface. Such piles may induce environmental concerns when the leachate seeping through the waste rock contains soluble metals, which may contaminate the subgrade. Assessing the hydrogeological response of a waste rock pile is a challenge because of the complex internal structure created by the construction method. This paper presents a coupled approach for investigating water flow under unsaturated conditions through a large waste rock pile. The approach first consists of a geophysical investigation to define the main features of the pile. This is followed by numerical simulations of the unsaturated flow through the pile based on the results from the geophysical characterization. In the case presented here, the pile is deemed to include three main zones: a zone made of widely graded material near the top, a relatively fine-grained material at mid-height, and a much coarser material near the base of the pile. The main elements of the internal structure are used to construct the numerical model, including hydrogeological properties (expressed stochastically) determined in the laboratory and in the field. Some of the key results of the geophysical and hydrogeological investigation are presented in the paper.

RÉSUMÉ
Dans une mine, les roches stériles sont extraites pour accéder au gisement minéralisé. Ces matériaux grossiers, à granulométrie très étalée, sont généralement stockés dans des haldes à la surface. Ces haldes peuvent induire des problèmes environnementaux lorsque le lixiviat, qui s'infiltre dans la roche stérile, contient des métaux solubles qui peuvent contaminer la fondation. L'évaluation de la réponse hydrogéologique d'une halde a stériles représente un défi en raison de la structure interne complexe créé par la méthode de construction. Cet article présente une approche couplée pour évaluer l'écoulement de l'eau en conditions non saturées dans une grande halde. L'approche comprend d'abord une étude géophysiques pour définir les principales caractéristiques de la structure interne de la halde. Ensuite, on procède à une étude numérique de l'écoulement dans la halde à stériles sur la base de la caractérisation géophysiques. Dans le cas présenté ici, la structure interne de la halde inclus trois zones principales: une zone de matériau très étalé dans le haut de la halde, un matériau relativement fin à la mi–hauteur et un matériau plus grossier près de la base. Les principaux éléments de la structure interne sont utilisés pour construire le modèle numérique, incluant les propriétés hydrogéologiques (exprimées de façon stochastique) déterminées en laboratoire et sur le terrain. Certains résultats clé issus de cette étude géophysique et hydrogéologique sont présentés dans cet article.

1 INTRODUCTION

Waste rock piles are used to store the uneconomic rock that was removed to access the ore from a mine. These piles can be quite large, especially in the case of open-pit mines. Traditionally, waste rock is disposed of in the most efficient and least costly manner possible. The content of most piles is not well known, or characterized, because these are deemed to bear little significance for the mine operation. Besides, some rock piles tend to create potential problems, such as acid mine drainage (AMD), leaching of heavy metals, and slope stability concerns. These problems are related to the flow of water through the waste rock. It is thus important to be able to evaluate water motion and distribution in such piles.

A waste rock pile is, by nature, a very heterogeneous system, comprising various features at different scales. The internal structure within the pile has a significant influence on how water (and air) flows in the waste rock. The waste rock grain size can vary from clayey and silty size particles to meter-sized blocks (e.g. Barbour et al. 2001; Nichol 2002; Azam et al. 2007). By itself, this widely spread gradation can create significant heterogeneity in the pile, which can be further increased by the construction method used. The placement technique of the waste rock influences the material properties and related moisture distribution in the pile. For instance, the fine grained materials, observed locally, typically shows a larger surface area, a higher water retention capacity, and a lower saturated hydraulic conductivity than the coarser waste rock. Such differences directly impact water flow. To assess the influence of these factors, it is essential to characterize the composition and the relavant property distribution within piles, which is not an easy task. It is often necessary to combine several tools, which provide information on the hydrogeological, geotechnical and geochemical characteristics of the waste rock (Aubertin et al. 2002, 2005, and 2008).

Geophysical tools are particularly interesting because they can lead to a three dimensional mapping of physical properties and their variations. Geophysical properties, such as electrical resistivity or dielectric constant, are known to be correlated with several hydrogeological and geochemical parameters, so they can provide indications of materials characteristics (in terms of grain size, porosity, degree of saturation, mineralogical composition, etc.). However, there is relatively few published works on the use of geophysical methods for the characterization of waste rock piles constructed on mine sites. Some of these limited studies present the use of electrical resistivity measurements for imaging acid leachate plumes (Campbell et al. 1999; Campbell and Fitterman 2000; Smith et al. 2001). DeVos et al. (1997) and Patterson (1997) present cases of direct delineation of AMD with the help of electromagnetic (EM) methods and DC resistivity. More recently, Poisson et al. (2009) and Anterrieu et al. (2010) investigated the internal structure of a 25 m-high waste rock pile located on a polymetallic mine site using electrical resistivity imaging, ground penetrating radar, and electromagnetic conductivity techniques. Laboratory testing was also undertaken on samples taken from exploratory trenches dug into the top surface in order to ascertain their geochemical and hydrogeological properties. The geophysical surveys indicated a general horizontal layering in the core of the pile and dipping stratifications parallel to the slope along the edges. These features were deemed to be related to the method of construction, and to a lesser extent, the waste rock characteristics. The results confirmed that such geophysical investigations can provide valuable information to assess the composition of a waste rock pile.

Assessing water flow in such piles is not straightforward either, because of the factors mentioned above and also due to the size of the domain and the non-linear response of the materials. Using numerical simulations of unsaturated flow, Fala et al. (2002, 2003, and 2006) have shown that a small change in water saturation, due to variations in local characteristics, can significantly affect the flow field within waste rock piles. Sometimes this results in preferential flow in higher saturation regions. These simulations also showed that fine-grained layers, horizontal or inclined downward toward the outer pile boundary, can channel flow inside or away from the interior through a process known as capillary barrier effect. Other studies have also shown that the distribution of water within a waste rock pile largely depends on its internal structure. (e.g. Smith et al. 1995; Lefebvre et al. 2001; Nichol 2002; Tran et al. 2003).

The main objective of this paper is to present a combined hydrogeological-geophysical approach to evaluate the unsaturated flow in a large waste rock pile. The study was performed on a mine site located in the eastern part of Québec (Canada), which is facing a metal leaching problem. The main details of the geophysical methods and the numerical calculations are presented below with some key results.

2 PILE DESCRIPTION

The pile investigated has an area of 900 000 m^2 and a maximum height of 110 m. The waste rock in the pile consists mainly of anorthosite (gangue) and hemo-ilmenite (ore). The cut-off grade at the mine is relatively high, so the waste rock pile may still contain fairly large ore content. The geophysical measurements were made in the surficial central part of the pile.

The conceptual pile model representation shown in Figure 1 has a width of 260 m and a height of 109 m. The surface is opened to the atmospheric conditions. The base of the pile consists, on the right (Fig. 1), of an impervious rock, and of the water table on the left (for the rest of the pile, which is under water). The impervious boundary condition imposed on the right hand side of the pile represents a vertical line of separation for the flow net inside the pile. In the simulations presented below, the residual water content is used to establish the initial condition for each calculation (based on in situ measurements). The climatic conditions (precipitation – evaporation cycles) used in this study are based on the monthly average values provided in Fala et al. (2003, and 2006), which analyzed the flow in a pile on a different mine site (in western Quebec). In these simulations, the imposed infiltration is about 40 cm per year (which is somewhat larger than the actual field situation Line AA shown in Fig. 1 gives the location where the volumetric water content and vertical velocity profiles are provided.

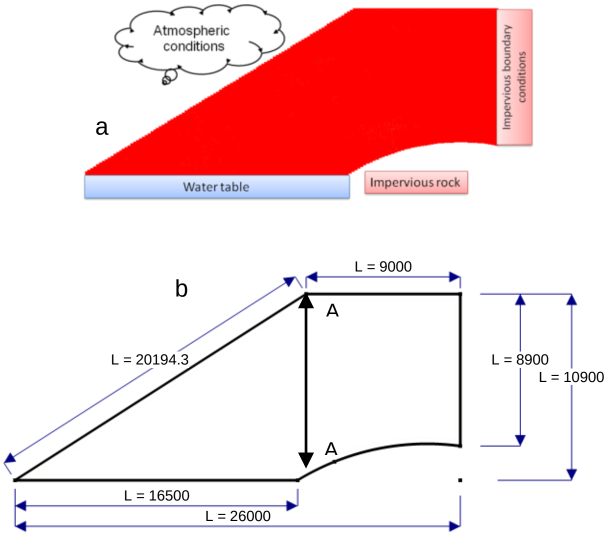


Figure 1. a) Boundary conditions; b) Geometry of the waste rock pile. Line AA (profile location) is located at x = 170 m and line BB is located 1 m above the base of the pile (i.e. the water table).

3. GEOPHYSICAL INVESTIGATION OF THE PILE

The geophysical work includes two main parts. The first component comprised laboratory measurements of electrical properties of the waste rock samples. The second component involved a series of electrical measurements on the pile at the mine site. These in situ measurements indicate the presence of complex features, such as thick layers of contrasting resistivity. Also, the field data confirmed the large concentration of metallic particles in the waste rock. A summary of results obtained from this investigation is presented here; more details are presented in Intissar (2009).

3.1 Laboratory measurements

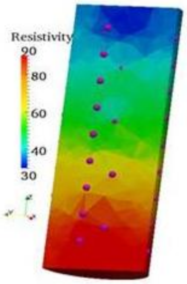
The purpose of the laboratory measurements was to evaluate the electrical properties of the waste rock as a function of the degree of water saturation and electrical conductivity of the interstitial fluid. These results help with the interpretation of the field measurements, especially in terms of the volumetric water content. The particle size distribution of the waste rock samples tested in the laboratory indicate that D_{10} = 0.012 cm and D_{60} = 0.36 cm, giving a coefficient of uniformity C_U (= D_{60}/D_{10}) of about 30. This reflects the widely graded distribution of this material. The very coarse fractions (> 10 cm) were left out of the samples. Before the column test was set up, the waste rock was moistened with deionized water to achieve a volumetric water content, θ, close to 0.04. Filling of the column was done one layer (about 4 cm thick) at a time; each layer was compacted to the selected condition before adding the next layer. The average porosity in the column after complete filling was about 24 %. Additional details on the column tests and measurements methods are presented in Intissar (2009).

Figure 2 shows a typical section of resistivity of the column obtained by 3D inversion of the collected data. It is seen that the resistivity of the material varies between 30 Ωm and 90 Ωm, and that it tends to increase from the top to the bottom of the column. This increase toward the base could be attributed to settlement that makes the material denser near the base. For this test, the resistivity of a water sample collected from the column was 3.1 Ωm. The 30-90 Ωm mentioned above is for the resistivity of the material consisting of waste rock saturated with electrolyte. 3.1 Ωm refers to the resistivity of the electrolyte in the pores. Interpretation of these data is based on Archie's law, which states that:

$$\rho_{mat} = \rho_w \,.\, \phi^{-m} \,.S_w^{-n} \qquad [1]$$

Where ρ_{mat} and ρ_w are respectively the resistivities of the material and of the pore fluid, and Φ and S are the porosity and the degree of saturation. Exponents m and n are close to 2. For ρ_w = 3.1 Ω.m, a porosity Φ of 24% and S = 1 (saturated), one obtains a resistivity ~ 54 Ω.m, which is in the measured range of 30-90 Ω.m.

This and additional measurements in the columns provided the required information for the analysis of the field data.



Resistivity distribution in the column: resistivity of pore water is 3.1 Ω.m.

Figure 2. Results of 3D inversion for resistivity data collected on the waste rock in the columns test.

3.2 Field measurements

The composition of the pile near the surface is of great importance since it largely controls rain and snow melt infiltration and runoff. The Syscal Pro 48 electrodes, with the dipole-dipole configuration and 16 levels were used to investigate the near surface. Electrical resistance tomography (ERT) measurements were conducted with electrode spacing of 2 m, giving a maximum investigation depth of about 8 m. Four ERT lines (L1, L2, L3, and L4), with a 6 m spacing, are shown in Figure 3. These measurements were inverted using the software Res2Dinv (Loke and Barker, 1996). The fit between the calculated and observed responses is excellent (RMS < 3%).

Resistivity values estimated from the field survey are larger than those measured in the laboratory. This could be caused by differences in grain size distribution. Laboratory measurements were carried out on material with a maximum grain diameter of 10 mm, while the field grain size can reach tens of centimetres. In addition, the surficial layers have undergone years of exposure with several cycles of leaching comparatively to the "fresh" waste rock used in the laboratory tests.

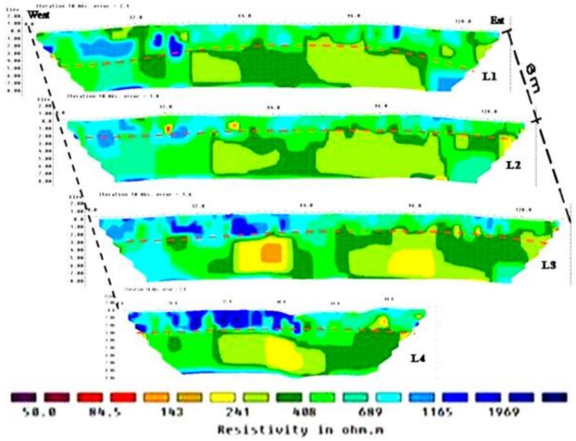


Figure 3. Resistivity models resulting from 2D inversion of ERT lines (L1, L2, L3 and L4) separated by a distance of 6 m.

For deeper imaging, a dipole–dipole configuration was used with a minimum spacing of 10 m and 25 levels. Profiles are 470 m long, with a 20 m separation between the lines. Figure 4 shows the resistivity model for the parallel lines L1NW-SE, L2NW-SE, and L4NW-SE. Data fits are good (<6%) for the back calculated resistivity.

Based on these results (and on chargeability data, not shown here), three major geoelectrical units are identified over the maximum investigated depth of about 70 m. These consist of a shallow heterogeneous layer, with a thickness of about 30 m and relatively high resistivities of 300 Ωm - 900 Ωm. Within this surface layer, some anomalies, either resistive or conductive, are observed, indicative of the heterogeneous nature of the material. The shallow layer is underlain by a conductive layer (80 - 250 Ωm) that is about 25m thick. This layer may result from the disposal conditions and origin of the waste rock at the time of construction. This waste rock may contain more fine particles, and thus retain more moisture. Higher water content in this layer may also be the result of the natural motion of the successive wetting fronts that follow seasonal snow melts and precipitations that occur on the mine site. The drop in resistivity for this layer can also be due to a large mineralization of the waste rock (as confirmed by high chargeability).

The third layer is highly resistive (> 1500 Ω.m) and appears more or less homogeneous. This layer might include conductive structures, which were not identified by the homogenization processes used in the calculations. Parametric analyses show that the sensitivity is weak for depths greater than about 50 m. As this layer was placed at the beginning of the mine operation, it probably consists of very coarse waste rock extracted near the ground surface to reach the ore zone. Other features obtained from the geophysical measurements on the waste rock pile are presented in Intissar (2009).

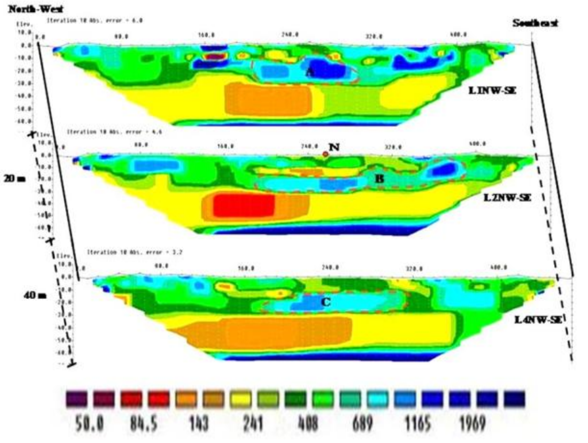


Figure 4. Resistivity models for 3 parallel surveyed lines (L1NW-SE, L2NW-SE, and L4NW-SE). The reddish color indicates conductive areas while blue indicates resistive areas. Maximum depth extent is approximately 70m.

4. SIMULATION OF UNSATURATED WATER FLOW

The results from the geophysical investigation of the internal structure of the large waste rock pile were used to assess the main characteristics of the water distribution and movement inside this pile. The finite element code HYDRUS-2D/3D (version 1; Simunek et al., 2007) was used for this purpose. The code relies on Richards (1931) equation.

Figure 5 shows the internal geometry and the finite element mesh used to simulate the pile response. It is seen that there are three layers of dense material (M1, Table 2) in the upper zone of the pile (30 m thick); each is one meter thick and located at a different height inside the coarse material (M3, Table 2) in this upper zone. The second zone underneath consists of a 20 m layer with the hydrogeological properties of the intermediate material (M2, Table2). The bottom part of the pile is made of loose and coarse-grained material (M3, Table 2). The finite element mesh (made of approximately 18000 triangular elements) was generated automatically by the HYDRUS-2D code; the typical calculation time is around 24 hours on HP Compaq type computer (processor: 2.7 GHz and memory: 2 G_o).

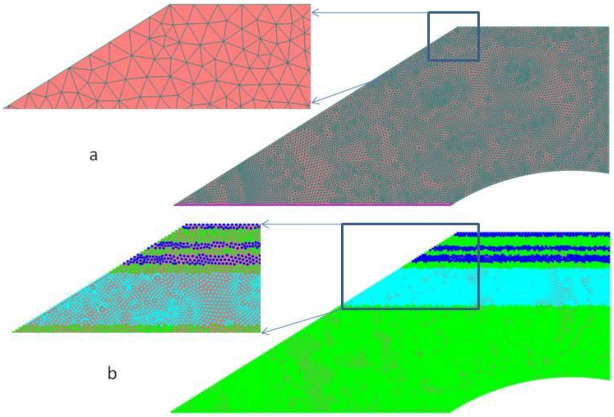


Figure 5. Example of finite element mesh (a) and material distribution (b)

Table 1. The van Genuchten (1980) model parameters

Material	θ_r	θ_s	α_v (cm^{-1})	n_v	K_s (cm/s)
M1	0.065	0.25	0.033	1.89	5×10^{-3}
M2	0.045	0.25	0.145	3.5	0.012
M3	0.045	0.25	4.93	2.19	0.35

M1: dense and fine; M2: intermediate; M3: loose and coarse.

4.1 Simulations with stochastical properties

Waste rock piles typically heterogeneous, even within a given characteristic zone. The influence of spatial variability of hydrogeological properties can be assessed by using a stochastic approach (Fala et al. 2008). In this case, it is assumed that the value of a given property at two locations depends on the distance between them; the closer they are, the closer their property values will be (on average). Two representative elemental volumes (REVs) in proximity are deemed to share somewhat similar depositional histories, which increases the probability of having similar properties (Miyazaki, 2006). This type of spatial variability of material properties can be handled statistically.

HYDRUS-2D/3D (Simunek et al., 2007) is used to assess the effect of spatial variability of the hydrogeological properties on the flow in the piles. This code generates a 2D-field of scaling factors related to the hydraulic conductivity K, suction (or pressure) h, and volumetric water content θ. Examples of such fields are illustrated in Figure 6, which shows horizontal, vertical and mixed correlations. Each point on Figures 6a, b, c indicates that K (or h, θ) values are multiplied by a specific scaling factor. The distance for which the scale factors are correlated depends on the correlation length ($1/\alpha_A$) along the horizontal and vertical directions. The input values of the van Genuchten (1980) model are regarded as average values with a standard deviation of "α_k" (for hydraulic conductivity), "α_h" (for suction), and "α_θ" (for volumetric water content). The actual values vary according to a selected spatial distribution for K and/or h and/or θ. In addition to the average values for the model parameters and their standard deviations, correlation lengths are also required as input data (i.e. spatial distribution of the hydrogeological characteristics). The distribution then exhibits a strong correlation (or autocorrelation) along a preferential direction (horizontal, vertical, or mixed) when the scaling factors form parallel rows of similar values. This is somewhat equivalent to having "pseudo" horizontal, vertical, or oblique stratifications in the field. Such stratifications are known to exist in most waste rock piles (e.g. Aubertin et al. 2002, 2005; Anterrieu et al. 2010). The code assumes that the variability can be approximated by means of a set of linear scaling transformations which relate the hydraulic characteristics θ(h) and K(h) to reference characteristics θ*(h*) and K*(h*). The technique is based on similar media concept introduced by *Miller and Miller* [1956] for porous media that differ only in the scale of their internal geometry. The concept was extended by *Simmons et al.* [1979] to materials that differ in morphological properties, but which exhibit 'scale-similar' hydraulic functions.

Three independent scaling factors are embodied in HYDRUS. These three scaling parameters may be used to define the spatial variability of the soil hydraulic properties as follows [*Vogel et al.*, 1991]:

$$K(h) = \alpha_K K^*(h^*) \qquad [2]$$

$$\theta(h) = \theta_r + \alpha_\theta \left[\theta^*(h^*) - \theta_r^*\right] \qquad [3]$$

$$h = \alpha_h h^* \qquad [4]$$

For the most general cases, α_θ, α_h and α_K are independent scaling factors. Less general scaling methods arise by invoking certain relationships between α_θ, α_h and/or α_K. For example, the original Miller and Miller (1956) scaling procedure is obtained by assuming $\alpha_\theta = 1$ (with $\theta_r^* = \theta_r$), and $\alpha_K = \alpha_h^{-2}$. A more detailed discussion of the above scaling relationships (Eq. 2-4), and their application to heterogeneous materials, is presented by *Vogel et al.* [1991].

In the simulations with stochastic properties presented here, the value of the correlation length varies from 5 to 100 m. The choice of correlation length and its direction depends on the spatial distribution of the hydrogeological properties, which are related to the grain size distribution of samples taken in the field. The method of Miller and Miller [1956] is used with a logarithmic standard deviation of the hydraulic conductivity (log σ_k) equal to 1; the other properties are considered homogeneous (constant) for each domain. The statistical parameters for simulation S1 to S4 are given in Table 2. Because of space limitations, only the detailed results from Simulations S1 and S4 are presented here; results for Simulations S2 and S3 (not shown explicitly) are nonetheless describe to highlight their main features.

Table 2. Statistical parameters adopted in the simulations.

Identification	Type of correlation	$\mathrm{Log}_{10}(\sigma_k)$	K	
			Corr-x	Corr-z
S1	Uniform			
S2	mix	1	100	100
S3	horizontal	1	100	5
S4	vertical	1	5	100

Base Case (S1)

Figure 7 shows the simulation results after ten years, during which the boundary conditions (monthly infiltration) were repeated each year. It is seen that the values of the volumetric water content (θ) along line AA vary between 0.06 to 0.14 in the upper zone, while they are around 0.06 in the rest of the pile, except above the impervious rock at the base of the pile where θ = 0.11 (due to local accumulation of water). The average values for the volumetric water contents (θ) were 0.13, 0.07, and 0.065 in the upper, middle, and lower zones of the waste rock pile, respectively. These values appear as fairly uniformly distributed for each zone, although the presence of some localised flow is observed also. The water vertical velocities (v) along line AA are less than 0.35 cm/day except near the impervious rock at the base of the pile (where v > 40 cm/day). The cumulated water flux (for a unit width of 1m) through line BB (100 cm above the water table at the base of the pile) after ten years is 1690 m^3/m length.

Mixed correlation (S2)

Simulation S2 represents a mixed correlation case with the following stochastic parameters: log (σ_K) = 1, corr-x = 100 m and corr-z = 100 m (Table 2). The simulation results after ten years are shown in Figure 8. It is seen that the values of the volumetric water content (θ) along line AA varies between 0.06 and 0.16 in the upper zone, while it is around 0.07 (near the residual value) in the rest of the pile, except above the impervious rock (where θ = 0.13).

Water vertical velocities (v) along line AA are less than 0.35 cm/day except near the base of the pile (where v = 33 cm/day). The cumulated water flux through line BB (1 m above the water table) for ten years is 1588 m^3/m length. Although there are some differences in the details of the water distribution between cases S1 and S2, the results indicate that the stochastic analysis does not significantly change the total flow at the base of the pile.

Horizontal correlation (S3)

Simulation S3 with preferred horizontal correlation was conducted with the following stochastic parameters: $\log_{10}(\sigma_K) = 1$, corr-x = 100 m and corr-z = 5 m (as shown in Table 2). The simulation results after ten years (not shown here) indicate that the value of the volumetric water content (θ) through line AA varies between 0.06 and 0.18 except above the impervious rock at the base where θ = 0.13 due to the local accumulation of water. The values of θ vary between 0.18 and 0.7 in the upper zone of the pile, while the values are around 0.08 in the middle and lower zones. These values are uniformly distributed in each zone, except for some localized flow areas.

The water vertical velocities (v) along line AA are less than 0.35 cm/day except near the impervious rock base (where v = 27 cm/day). The cumulated water flux through line BB (1 m above the water table at the base of the pile) for ten years is 1549 m^3/m length. When compared to the previous cases (S1 and S2), the horizontal correlation does not produce significant differences on the water distribution inside the pile or on the amount of water reaching the bottom.

Vertical correlation (S4)

Simulation S4 with preferred vertical correlation was conducted with the following stochastic parameters: $\log(\sigma_K) = 1$, corr-x = 5 m and corr-z = 100 m (Table 2). The simulation results after ten years (not shown) indicate that the values of the volumetric water content (θ) along line AA vary between 0.06 and 0.18 in the upper zone, while these are around 0.07 in the rest of the pile except near the impervious rock (where θ = 0.14). The values of θ tend to decrease from the right to the left of the pile. Also, the volumetric water content at the center of the third zone (60 m thick) is smaller than the right and left sides' boundaries. The number of localized flow areas is greater than that of the other cases. The water vertical velocities (v) along line AA are less than 0.3 cm/day except at the base of the pile (where V = 29 cm/day). The cumulated water flux through line BB (at the base of the pile) for ten years is 1403 m^3/m length. When compared with the base and horizontal correlation cases, the vertical correlation case shows more significant effects with localized distribution inside the pile and water vertical velocities. The amount of water flux at the bottom of the pile in the vertical correlation case is close to those obtained for the base and horizontal correlation cases.

When the four simulations are compared, it is seen that the main differences are in the details of where water accumulates and flows. However, the amount of cumulative water flux to the water table remains relatively unchanged for these four cases.

5. DISCUSSION AND CONCLUSION

The composition identified by the geophysical methods is used in the numerical simulations of water movement through the waste rock pile. The calculated values obtained for the volumetric water contents are close to that determined from the geophysical investigation. Stochastical correlations are used here to reflect the heterogeneity of the material in each zone. However, the results show that there are no major effects of the correlation factor on water movement and flux. This may be due to the large size of the pile (260 m x 110 m). Other stochastical parameters are being considered to better reflect the heterogeneity of the pile; these results will be presented nearly elsewhere.

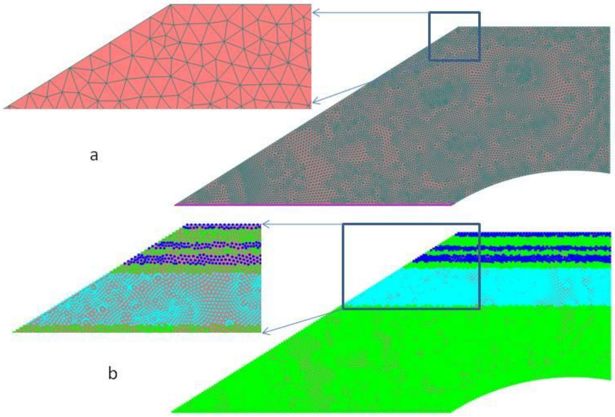


Figure 5. Example of finite element mesh (a) and material distribution (b)

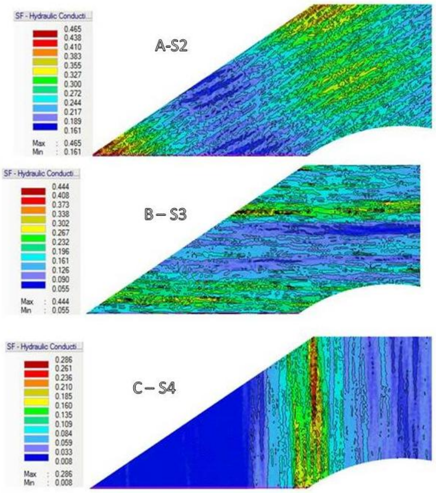


Figure 6. Stochastic distribution of hydraulic conductivity, A: mixed correlation (simulation S2), B: horizontal correlation (simulation S3), and C: vertical correlation (simulation S4)

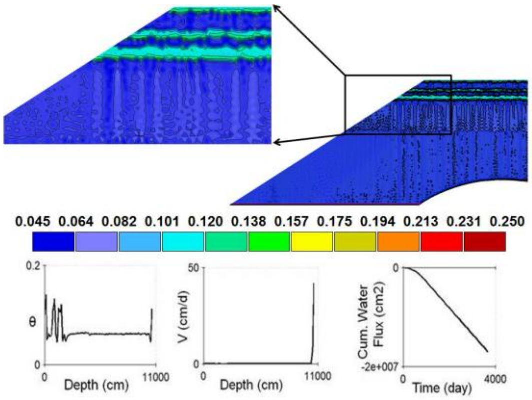


Figure 7 . Results for simulation S1 (base case), in terms of contours of θ, values of θ along line AA, vertical velocity along line AA, and cumulative flux at the base (along line BB).

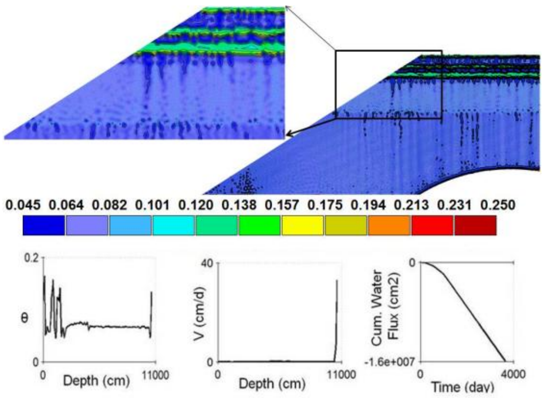


Figure 8 . Results for simulation S2 (mixed correlation)

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References

Anterrieu, O., Chouteau, M. and Aubertin, M., 2010. Geophysical characterization of the large-scale composition of a waste rock pile from a hard rock mine. *Bulletin of Geological Engineering and the Environment*, 69: 533-548.

Aubertin, M., Fala O., Bussière, B., Martin, V., Campos, D., Gamache-Rochette, A., Chouteau, M. and Chapuis, R. 2002. Analyse des écoulements de l'eau en conditions non saturées dans les haldes à stériles. *Symposium sur l'Environnement et les Mines, Rouyn-Noranda, CD-ROM. CIM.*

Aubertin, M., Fala, O., Molson, J., Gamache-Rochette, A., Lahmira, B., Martin, V., Lefebvre, R., Bussière, B., Chapuis, R. P., Chouteau, M., Wilson, G.W. 2005. Évaluation du comportement hydrogéologique et géochimique des haldes à stériles. *Symposium Rouyn-Noranda: l'Environnement et les Mines, Rouyn-Noranda, CD-ROM, CIM.*

Aubertin, M., Fala, O., Molson, J., Chouteau, M., Anterrieu, O., Hernandez, M. A., Chapuis, R. P, Bussière, B., Lahmira, B., Lefebvre, R. 2008. Caractérisation du comportement hydrogéologique et géochimique des haldes à stériles. *Symposium sur l'environnement et les mines, Rouyn-Noranda, Canada. CIM.*

Barbour, S. L., Hendry, M. J., Smith, J. L., Beckie, R.D., Wilson, G. W. 2001. A research partnership program in the mining industry for waste rock hydrology. *University of Saskatchewan, Canada.*

Bussière, B., Benzaazoua, M., Plante, B., Pepin, G., Aubertin, M., and Laflamme, D. 2008. Evaluation of the geochemical behavior of the Lac Tio mine waste rocks, Havre-St- Pierre, Quebec (in French). *Symposium Environment and Mines, Rouyn-Noranda, Quebec, CD-ROM, CIM.*

Campbell, D. L., Horton, R. J., Bisdorf, R. J., Fey, D.L., Powers, M. H., Fitterman, D. L. 1999. Some geophysical methods for tailings/mine waste rock. *Tailings Mine Waste 99:35–43*

Campbell, D. L., Fitterman, D. V. 2000. Geoelectrical methods for investigating mine dumps. *ICARD 2000–Proceedings from the fifth international conference on acid rock drainage, pp 1513– 1523*

DeVos, K.J., Pehme, P., Greenhouse, J.P., 1997. Ground geophysical surveys for mine wastes. *In: Gubins, A.G. (Ed.), Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration, pp. 917–926. 1997.*

Fala, O., 2002. Étude des écoulements non saturés dans les haldes à stériles à l'aide de simulations numériques. *Mémoire de maîtrise en génie minéral, École Polytechnique de Montréal, Canada.*

Fala, O., Aubertin, M., Molson, J. W., Bussière, B., Wilson, G. W., Chapuis, R., Martin, V., 2003. Numerical modeling of unsaturated flow in uniform and heterogeneous waste rock piles, In: *Proc Sixth Int Conf Acid Rock Drainage (ICARD), Australasian Institute of Mining and Metallurgy, Cairns, Australia, pp 895–902*

Fala, O., Molson, J., Aubertin, M., Bussière, B., Chapuis, R. P. 2006. Numerical simulations of long term unsaturated flow and acid mine drainage at waste rock piles. *In: Barnhisel RI (ed) Proc of the 7th Int Conf Acid Rock Drainage (ICARD), 26–30 March 2006, St. Louis, Missouri, The American Society of Mining and Reclamation, pp 582–597.*

Helgen, S., Davis, A., and Byrns, C., 2000. Measurement of oxygen, temperature and geochemical profiles in sulphide and oxide waste rock dumps of different ages. In: *Proceedings; Fifth International Conference on Acid Rock Drainage, Society for Mining, Metallurgy and Exploration, Inc., Littleton, U.S.A.*

Intissar, R., 2009. Apport des méthodes électriques à la détermination de la structure interne d'une halde à stériles. *Mémoire de maîtrise en génie minéral, École Polytechnique de Montréal, Canada.*

Lefebvre, R., Hockley, D., Smolensky, J., Lamontagne, A, 2001. Multiphase transfer processes in waste rock pile producing acid mine drainage, 2: Applications of numerical simulations. *J. of Contaminant Hydrology, 52 (1-4), 165-186.*

Loke, M.H., Barker, R.D., 1996. Rapid least-square inversion of apparent resistivity pseudo-sections by a quasi-Newton method. *Geophysical Prospecting, 44, 2, 131-152.*

Miller, E. E., and Miller, R. D., 1956. Physical theory of capillary flow phenomena, *J. Appl. Phys., 27, 324–332.*

Nichol, C. 2002. Transient flow and transport in unsaturated heterogeneous media: field experiments in mine waste rock. *Ph.D thesis, University of British Columbia, Canada.*

Newman, L.L., Herasymuik, G.M., Barbour, S.L., Fredlund, D.G., Smith, T., 1997. The hydrogeology of waste rock dumps and mechanism for unsaturated preferential flow. *Proceedings of the 4th Int Conf on Acid Rock Drainage (ICARD). Vancouver, BC. Natural Resources Canada, Ottawa, vol. 2, pp. 551–564.*

Pepin, G., 2009. Evaluation of the geochemical behavior of waste rocks potentially generating contaminated neutral drainage, using experimental test cells in situ. *M. Sc., Mineral Engineering, École Polytechnique of Montreal (UQAT). December 2006, 136 pages (in French).*

Poisson, J., Chouteau, M., Aubertin, M., Campos, D., 2009. Geophysical experiments to image the shallow composition and the moisture distribution of a mine waste rock pile. *Journal of Applied Geophysics 67: 179–192 (doi: 10.1016/j.jappgeo.2008.10.011).*

Price, W.A., 2003. The mitigation of acid rock drainage: Four case studies from British Columbia. *In: Proc Sudbury 2003: Mining and the Environment, CD-ROM, pp.1121*

Richards, L.A., 1931. Capillary conduction of liquids in porous mediums. *Physics,* 1- , pp. 318–333.

Ritchie, A.I.M., 1994. The waste rock environment. *Chapter 5 In: Jambor, J.L. and Blowes, D.W. (Eds.), Short Course Handbook on Environmental Geochemistry of Sulfide Mine Wastes, Mineralogical Association of Canada, Waterloo, Ontario, pp. 133-161.*

Ritz, M., Robin, H., Pervago, E., Albouy Y., Camerlynck, Cristian., Descloitres, M., Mariko, A., 1999. Improvement to resistivity pseudosection modelling by removal of near-surface inhomogeneity effects: application to a soil system in south Cameroon. *Geophysical Prospecting 47: 85-101.*

Simunek, J., Sejna, M., and Van Genuchten, M. T., 2007. The HYDRUS-2D software package for simulating the two dimensional movement of water, heat, and multiple solutes in variably- saturated media. *Version 2.0. U.S. Salinity Laboratory.*

Simmons, C.S., Nielsen, D.R., and Biggar, J .W. 1979. Scaling of field-measured soil-water properties. *Hilgardia, Vol. 47, p. 77-174.*

Smith, L., lopez, D. L., Beckie, R., Dawson, R. and Price, W., 1995. Hydrogeology of waste rock dumps. *Final Report to Natural Resources Canada, Contract 23440-4-1317/01-SQ, MEND Report PA-1, Natural Resources Canada.*

Smith, B. D., Campbell, D. L., Wright, W.G., 2001. Using resistivity to map acidic waters at the May Day mine dump*. In: Proc SAGEEP 2001, Silverton, Colorado, 12 p.*

Tran, A. B., Fines, P., Miller, S. Williams, D., Wilson, W., 2003. Hydrologic and geochemical characterization of two full-scale waste rock piles. *Geotechnical News, Sept. 03: 36-42.*

Van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44 (1980), pp. 892–898.

Vogel, Cislerova, L., M., and Hopmans, J. W. 1991., Porous media with linearly variable hydraulic properties. *Water Resour. Res*., *27*(10), 2735–2741