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Numerical simulations of water flow and contaminants transport near mining wastes disposed in a fractured rock mass

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ABSTRACT

A numerical tool, called Hydro-Geosphere, was used to simulate unsaturated water flow and contaminants migration around an open pit filled with mining wastes. Numerical simulations had been carried out to assess the influence of various factors on water flow and solute transport in and around the surface openings including recharge, properties of the waste material and presence of fractures in the surrounding rock mass. The effect of the regional hydraulic gradient was also investigated. The analyses were conducted by simulating various 2D cases using experimentally obtained material properties and controlled boundary conditions. The effects of the hydrogeological properties of the filling material (i.e., water retention curve and hydraulic conductivity function), fracture network characteristics and conductivity of the joints were assessed. The results illustrate that fractures control water flow and contaminants transport around the waste disposal area. A fracture network can desaturate the system and improve the regional gradient effect.

1. Introduction

The mining industry produces a large quantity of wastes which are usually disposed of in surface facility. Some of these wastes can also be returned in the mine itself as filling material. Such backfill, made of tailings or waste rocks, can be placed in open pits or in underground stopes [1]. One of the major environmental problems in this regard relates to the safe disposal of potentially toxic wastes, which migration to the biosphere must be controlled. This is a particular concern when sulphidic minerals are present in the tailings or waste rocks, because these may oxidise and generate acid mine drainage and metal leaching [2]. Isolation of the contaminants in low-permeability geologic media, where groundwater velocities are typically low and molecular diffusion is the primary contaminant migration process of importance, can appear as an advantageous solution. However, the presence of fractures in the medium can greatly influence the mass transport process because such discontinuities may represent preferential pathways for rapid contaminants migration [3–5].

A number of mathematical models describing groundwater flow and contaminants transport in fractured porous media have been developed. One classical approach is to consider the fractured porous medium as an equivalent porous medium in which spatial variations in hydrogeological properties of the rock mass are averaged over a representative elementary volume (REV). As it will be illustrated below, this approach can become a source of imprecision in estimating contaminant concentrations and migration plume. Another approach is based on discretely fractured conceptualization of the rock mass, for which the geometry and hydraulic properties of each fracture can be specified explicitly. The latter approach is used by the Hydro-Geosphere code [6], which was applied for this investigation. In addition to flow in fractures, the Hydro-Geosphere code can also incorporate matrix diffusion by using the principle of superposition of one-dimensional fracture elements onto two-dimensional porous matrix elements.

Combined with Hydro-Geosphere, this paper presents the results of numerical simulations of the unsaturated flow and contaminants transport from mining wastes disposed of in an open pit and underground excavation, and the rock mass without or with fractures is taken into account. This numerical code is based on the Frac3DVS and Hydro-Sphere models, and it solves variably-saturated and multi-component transport in discretely fractured porous media [6]. A brief description of the code, governing equations and material properties are presented. Simulations results for a symmetric open pit with a regional hydraulic gradient (in 2D) are then presented and discussed. The effects of waste material characteristics and fracture network are investigated.

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2. Hydro-Geosphere code

The numerical code Hydro-Geosphere [6] was used for all simulations presented here. This code is based on a three-dimensional control volume finite element model that simulates variably-saturated subsurface flow and advective–dispersive mass transport in discretely-fractured or non-fractured porous media. The model simulates flow and transport in 3D porous medium and in 2D fractures here.

Variably-saturated flow is described by a modified form of Richards' equation, where the storage term is expanded to consider water and soil compressibility [4]. Fractures are idealized as two-dimensional parallel plates, with uniform total head and concentration across the fracture width. The flow velocities in the discontinuities are determined by the commonly used cubic law [7]. Retention and relative permeability curves for both the fractures and the matrix can be expressed from van Genuchten's function [8] or can be specified in a tabular form. In the model, the porous medium is discretized with 3D finite elements and fractures are discretized with 2D finite elements. Nodes forming the 2D fracture elements are common with nodes. It is assumed that there is continuity of hydraulic head and concentration in the fracture and matrix at these common nodes, which corresponds to instantaneous fluid and solute exchange between the domains.

For solute transport, the model assumes linear equilibrium sorption is independent of the sorption capacity of the medium, the flow velocity, or the solute residence time. Sorption is described by a retardation factor for the fracture (R_f) and for the matrix (R), respectively. The effective diffusion coefficient for solutes in the matrix is given by the free water diffusion coefficient and tortuosity. Mechanical dispersion in the fractures and matrix is described by the longitudinal and transverse dispersivities. For transverse dispersivity in the 3D porous medium, Hydro-Geosphere accounts for a horizontal and a vertical component [9].

Hydro-Geosphere can be used to conduct simulations with relatively short computing times and high efficiency; and other characteristics of the code are described elsewhere [4,6].

3. Governing equations

3.1. Water flow in a single fracture

As mentioned above, water flow in fractures is described by the cubic law which is an analytical solution of the Navier–Stokes equation for laminar, steady state water flow between two planar surfaces. This law can be written as follows [10–11]:

$$Q_f = V_f \times A_{\mathrm{sec}} = -\left(\rho_w g b^3 \omega \Delta h\right)/12\mu_w L\right) \tag{1}$$

$$A_{sec} = b \times w \tag{2}$$

where Q_f is the fracture discharge, m^3/s; V_f the mean water flow velocity in fracture, m/s; A_{sec} the area of fracture perpendicular to water flow, m^2; b the fracture opening, m; w the fracture width perpendicular to water flow, m; L the fracture length parallel to water flow, m; Δh the hydraulic head difference along the flow direction, m; ρ_w the water density, kg/m^3; g the gravity acceleration, m/s^2; and μ_w the water dynamic viscosity, kg/(m s).

Eq. (1) can be modified with additional parameters by taking into account influence factors such as surface roughness, tortuosity, and Reynolds number [12–13].

For transient and partially saturated water flow conditions, Eq. (1) can be used to determine the continuity equation of flow discharge and the equation of partially saturated water flow in fractures [14]. Under these conditions, the unsaturated hydraulic functions of the materials and fractures must be defined.

3.2. Unsaturated water flow

The above mentioned cubic law can be used to obtain the water flow equation under unsaturated transient flow conditions. This expression can be written as follows [4];

$$-\left[\frac{\partial}{\partial x}\left[\left(\frac{\rho g e^3}{12\mu}\right)K_{rx}(\Psi)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\frac{\rho g e^3}{12\mu}\right)K_{ry}(\Psi)\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\frac{\rho g e^3}{12\mu}\right)K_{rz}(\Psi)\frac{\partial h}{\partial z}\right]\right]=\frac{\partial\theta_f(\Psi)}{\partial t} \tag{3}$$

where $K_r(\Psi)$ is the relative hydraulic conductivity of the fracture (value between 0 and 1) as a function of suction Ψ (negative pressure) along the three Cartesian axes (x, y, z); $\theta_f(\Psi)$ the volumetric water content of the fracture which is also a function of suction, m^3; and e the fracture aperture, m.

3.3. Contaminants transport

Contaminants transport in fractured rock is an important but difficult aspect to consider due to the complexity of fracture networks and the important role of fractures on affecting contaminants migration. For most reactive and non-reactive contaminants, the principal transport modes are advection and hydrodynamic dispersion, which includes molecular diffusion and mechanical dispersion.

Advection controls the migration by water flow in response to a hydraulic gradient. Mechanical dispersion is due to a concentration gradient, and it takes into account tortuosity of the medium.

In order to describe contaminants transport in a discretely-fractured porous medium, two equations are needed for the porous matrix and for the fractures, respectively. Three-dimensional transport in a variably-saturated porous matrix is described by the following equation [15]:

$$\theta_s S_w \frac{\partial c}{\partial t} + q_i \frac{\partial c}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\theta_s S_w D_{ij}\frac{\partial c}{\partial x_j}\right) + \theta_s S_w c = 0 \tag{4}$$

$i, j = 1, 2, 3$

where c is the contaminant concentration, mol/L; D_{ij} the hydrodynamic dispersion coefficient, m^2/s; q_i the fluid flux, m^3/s; θ_s the porosity,%; S_w the degree of (water) saturation,%; and the hydrodynamic dispersion coefficient D_{ij} is given as follows [14]:

$$\theta_s S_w D_{ij} = (\alpha_L - \alpha_T)\frac{q_i q_j}{|q|} + \alpha_T |q| \delta_{ij} + \theta_s S_w \tau D_d \delta_{ij} \tag{5}$$

where α_L and α_T are the matrix longitudinal and transverse dispersivities, m, respectively; $|q|$ the magnitude of the Darcy flux, m/s; τ the matrix tortuosity; D_d the free solution diffusion coefficient, m^2/s; and δ_{ij} the Kronecker delta. The effective diffusion coefficient D_e for solutes transport in the matrix is given by free water diffusion coefficient and tortuosity, τD_d. Typical values for the diffusion coefficient D_0, under saturated conditions in soils, range between 1×10^{-9} and 2×10^{-9} m^2/s [15]. The tortuosity coefficient usually varies between 0.01 and 0.5 [16]. Mechanical dispersion in the fractures and the matrix is described by longitudinal and transverse dispersivities. Hydro-Geosphere accounts for a horizontal and a vertical component of the transverse dispersivity in the 3D porous medium. Other equations similar to Eqs. (4) and (5) can be written to describe contaminant transport in the variably-saturated fracture.

4. Conceptual model of open pit

Combined with the Hydro-Geosphere, Fig. 1 presents the conceptual 2D model of an open pit filled with mining wastes. The open pit is symmetric about the vertical axis located at

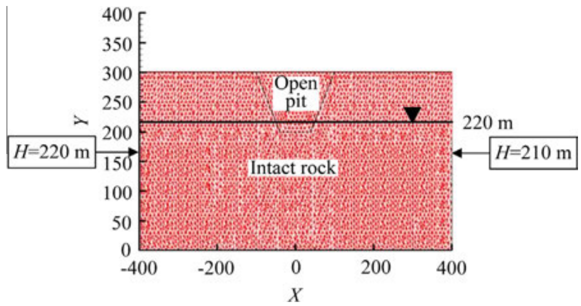

Fig. 1. Conceptual model of the open pit mine (in 2D) excavated in a homogeneous rock mass with the finite element mesh.

$x = 0$ m. It has a depth of 100 m and the wall slope angle is 68° from the horizontal axis. The lower limit of the model is 200 m below the pit base. The model spreads horizontally from $x = -400$ m to +400 m. These dimensions are typical for the open pit mine surrounded by hard rock in the region of Abitibi, Québec, Canada.

The unsaturated flow and contaminants transport are studied for two types of waste materials. One is the coarse-grained waste rocks resulting from mining operations. And the other is fine-grained tailings from the milling process. The typical characteristics of these waste materials have been described elsewhere [2,17–18].

It should be noted that water is pumped to the base of the pit while the open pit is operating. There is thus a drawdown of the phreatic surface surrounding the mine. Pumping stops at the end of the mining. Then there is a progressive rebound of the phreatic surface in and around the pit. In the simulations here, the natural rise of the water table, which is expected to take many years, even decades, is not taken into account. The water table rise here is due to the surface recharge from the local precipitation, rather than by the recovery of the natural conditions that existed before the mine.

The model grid was created with the grid builder software, being a 2D mesh generator tool. The mesh is made with a triangular finite elements, as shown in Fig. 1. This code generates a default mesh which can be refined by the user. For all the simulations shown here, a mesh with 8128 nodes and 7906 elements has been used.

4.1. Material hydrogeological characteristics

Water retention curves, as shown in Fig. 2, represent the variation of the saturation degree versus negative pressure (i.e., suction) for the tailings, waste rocks, intact rock and fractures. More specifically, Fig. 2 takes the saturation degree S_w as a function of the water pressure head with a semi-log plot. Table 1 lists the corresponding hydrogeological parameters for the various materials based on the van Genuchten (1980) equations. These parameters have been obtained from representative experimental data for waste rocks [17], tailings [18,19] and rock matrix [20]. And the data for fractures were extracted from the Hydro-Geosphere manual [6].

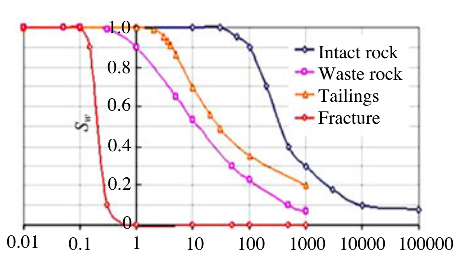

Fig. 2. Water retention curves for the different materials.

Table 1
Hydrogeological input parameters for the waste rocks, tailings and intact rock.

Hydraulic parameters	Waste rocks	Mill tailings	Intact rock
Porosity	0.34	0.43	0.02
Air entry value (head, m)	0.3	3.5	35
Saturated hydraulic conductivity K_{sat} (m/s)	1×10^{-5}	1×10^{-8}	3.2×10^{-8}
Residual volumetric water content θ_r	0.03	0.1	0.0015

Fig. 2 shows that the materials tend to desaturate with the negative pressure head increasing. The intact rock mainly remains at the higher saturation degree than the tailings and waste rocks because of its lower porosity and higher air entry value (AEV). This lower AEV means that the coarser waste rock starts to desaturate at a lower pressure head than the tailings or the intact rock. Also, Table 1 indicates that the intact rock and tailings have a somewhat similar saturated hydraulic conductivity, whereas the waste rocks are more pervious.

5. Simulation results

5.1. Open pit filled with waste rocks

The first series of simulations represent an open pit filled with a coarse-grained waste rocks. In these simulations, the initial water table is located at the elevation of 220 m (i.e., 20 m from the base of the pit). The regional hydraulic gradient is applied by decreasing the hydraulic head from 220 m (i.e., $x = -400$ m) to 210 m (i.e., $x = +400$ m), so that the regional gradient of 0.0125 is obtained. The left and right boundaries are pervious with fixed hydraulic heads of 220 m and 210 m, respectively.

The base of the model is impervious. A constant recharge rate of 1.5 mm/d is applied at the surface for 10 days, and it is followed by a period of 10 days without rain. This sequence is repeated for 20 years. For the contaminants migration, a constant unit concentration is fixed within the open pit, while it is initially zero elsewhere. The value of the free diffusion coefficient is 2×10^{-9} m^2/s. The transport model parameters are summarized in Table 2. For the open pit filled with two types of material, three cases are presented here: a homogeneous rock mass, a rock mass with vertical fractures and a rock mass with orthogonal fracture network. All simulations are conducted under unsaturated and transient flow conditions. Results were extracted from Hydro-Geosphere using the Tecplot package.

Case 1: homogeneous rock mass in open pit filled with waste rocks

Fig. 3 shows the simulated values of suction and saturation degree as a function of time t (10^{-3} days, 0.1 days, 5 days, 10 days, 100 days, 1000 days, and 10 years) and distance along a horizontal section located at $y = 280$ m for a non-fractured rock mass. Fig. 3 indicates that initial suction distribution is linear, varying between −60 m and −70 m for $x = -400$ m and +400 m. Over time the suction decreases greatly due to the precipitation, especially within the rock mass.

The simulation results also indicate that the variation of suction remains linear in the open pit, but not in the rock mass. With the

Table 2
Rock mass and fracture input parameters used in flow and transport simulations.

Parameters	Value
Rock mass tortuosity τ	0.1
Matrix longitudinal dispersivity α_l	0.1 m
Matrix transverse dispersivity α_t	0.01 m
Fracture longitudinal dispersivity α_{lf}	0.5 m
Fracture transverse dispersivity α_{tf}	0.05 m

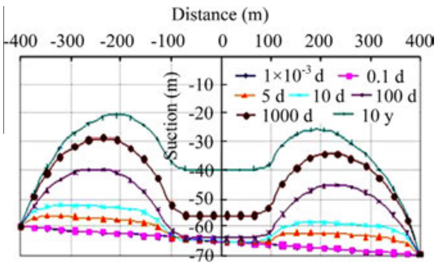

Fig. 3. Simulated pore water pressure head (suction) at $y = 280$ m in open pit filled with waste rocks in a homogeneous (non-fractured) rock mass (Case 1).

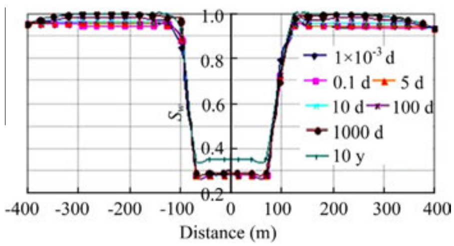

Fig. 4. Simulated values of the saturation degree at $y = 280$ m in open pit filled with waste rocks in a homogeneous (non-fractured) rock mass (Case 1).

imposed regional gradient, the pore water pressures are larger on the left side of the model than on the right side.

As shown in Fig. 4, the low porosity rock mass remains at a high saturation degree with values of S_w ranging between 90% and 100%, whereas the waste rocks have a much lower saturation degree (i.e., near the residual value). Nonetheless, it can be noticed that the saturation degree of the waste rocks increases with time, with S_w values climbing from 28% to 38%. Some water thus accumulates in the open pit.

Fig. 5 shows the results of contaminant concentration levels when the time t equals 10 days, 1000 days, 10 years and 20 years. This figure shows that the concentration remains constant (unity) inside the open pit (imposed condition). The extent of contaminant migration is relatively limited in the early simulation time. As time

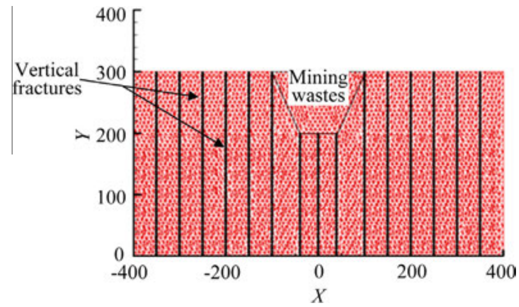

Fig. 6. Conceptual model of an open pit excavated in rock mass with vertical fractures of 0.3 mm of aperture (Case 2).

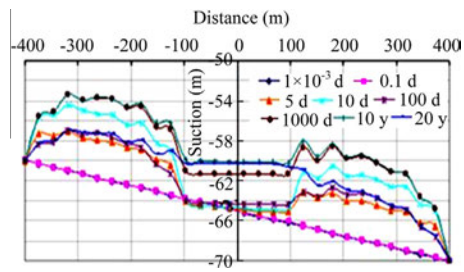

Fig. 7. Simulated pore water pressures (suction head) at $y = 280$ m in open pit filled with waste rocks in a rock mass with vertical fractures (Case 2).

increases, precipitations favor migration which becomes more significant especially at depth. Due to the fairly low value of the regional hydraulic gradient, the contaminant outlet is almost symmetric and mainly progresses downward.

Case 2: rock mass with vertical fractures in open pit filled with waste rocks

In this simulation, vertical fractures are introduced into the rock mass. The fractures of this model have a constant aperture of 0.3 mm and are located at $x = -350$ m, -300 m, -250 m, -200 m, -150 m, -100 m, -40 m, 0 m, 40 m, 100 m, 150 m, 200 m, 250 m, 300 m and 350 m (Fig. 6).

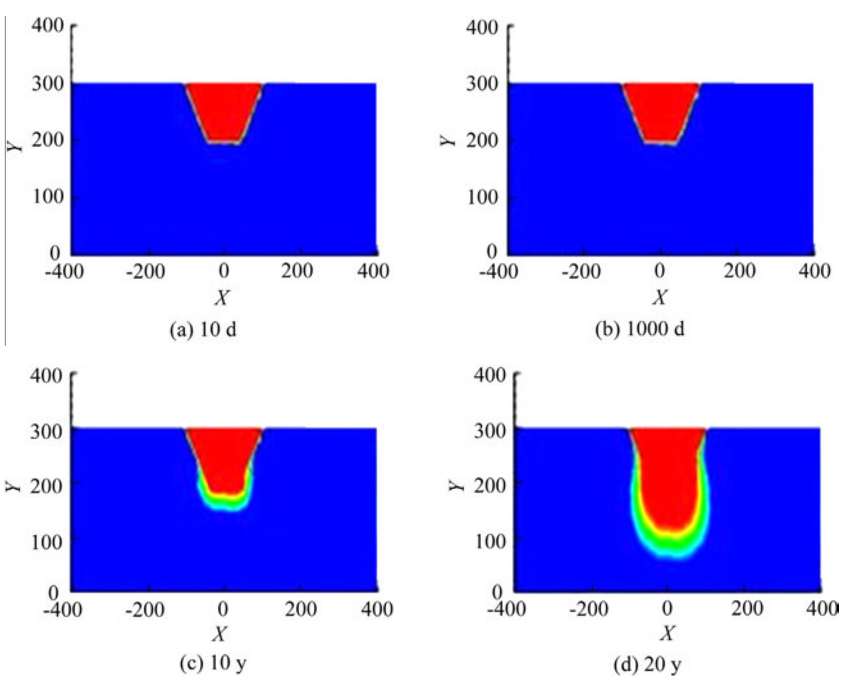

Fig. 5. Simulated contaminant concentration values at 10 days, 1000 days, 10 years and 20 years in open pit filled with waste rocks in a homogeneous rock mass (Case 1).

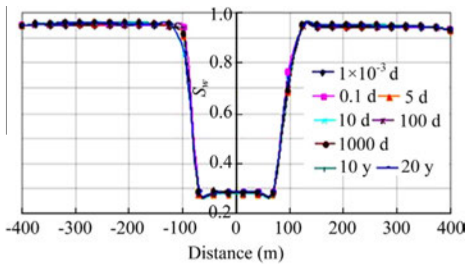

Fig. 8. Simulated saturation degree at $y = 280$ m in open pit filled with waste rocks in a rock mass with vertical fractures (Case 2).

Figs. 7 and 8 show the simulated distributions of suction and saturation degree as a function of time (10^{-3} days, 0.1 days, 5 days, 10 days, 100 days, 1000 days, 10 years and 20 years) and distance. Fig. 7 illustrates the effect of vertical fractures on suction head. It is seen that the initial suction distribution is linear. And then this distribution becomes irregular (i.e., wavy) over time due to the presence of the fractures. The variations of suction are less obvious in comparison with the homogenous (non-fractured) rock mass (Case 1). Fig. 8 shows that there is almost no variation of the saturation degree in the pit and rock mass. Hence, moisture does not tend to accumulate in the waste rocks due to the presence of these vertical factures and the high hydraulic conductivity in comparison with the homogeneous (non-fractured) rock mass.

The evolution of contaminants concentration with time is shown in Fig. 9, which shows a preferential migration through vertical fractures. As expected, contaminants follow the fractures and migrate rapidly to reach a greater depth within the simulated period. Contaminants migrate mainly through advection along the fractures here.

Case 3: rock mass with orthogonal fractures in open pit filled with waste rocks

In this case, the simulation includes an orthogonal fracture network in the rock mass. The fractures have an aperture of 0.3 mm, which is the same as vertical fractures. The horizontal fractures are located at $y = 30$ m, 60 m, 90 m, 120 m, 150 m, 180 m, 210 m, 230 m, 250 m, 270 m and 290 m (Fig. 10).

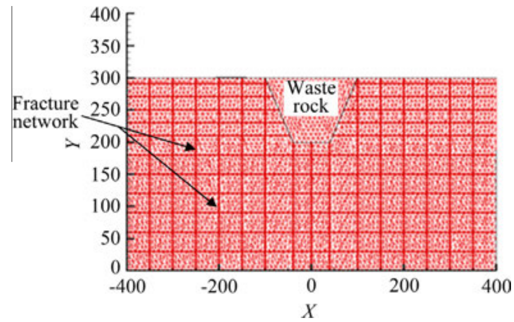

Fig. 10. Conceptual model of the open pit excavated in a rock mass with orthogonal fracture network (Case 3).

Figs. 11 and 12 show the results of simulated values of suction and saturation degree. It can be seen that the orthogonal fractures tend to amplify water flow in the network. Fig. 11 shows that the variation of the pore water pressure (suction head) inside the open pit is smaller than the two previous cases (i.e., homogenous rock mass and rock mass with vertical fractures).

Also, as shown in Fig. 12, the saturation degree remains almost constant with time. Hence, introducing such an orthogonal fracture network promotes drainage, and limits moisture accumulation in the pit due to increased water flow through the fracture network.

The evolution of the contaminants concentrations over time is shown in Fig. 13, which shows a obvious difference of the contaminant plume in comparison with the two previous cases (especially for the homogeneous rock mass).

Also, in contrast to Case 1, contaminants migrate more markedly along the regional gradient direction. Thus the risk of contamination would increase downstream in the fractured rock mass (i.e., Case 3).

5.2. Open pit filled with tailings

In this next simulations, the open pit is filled with finer grained mill tailings, which are much less pervious than waste rocks. The

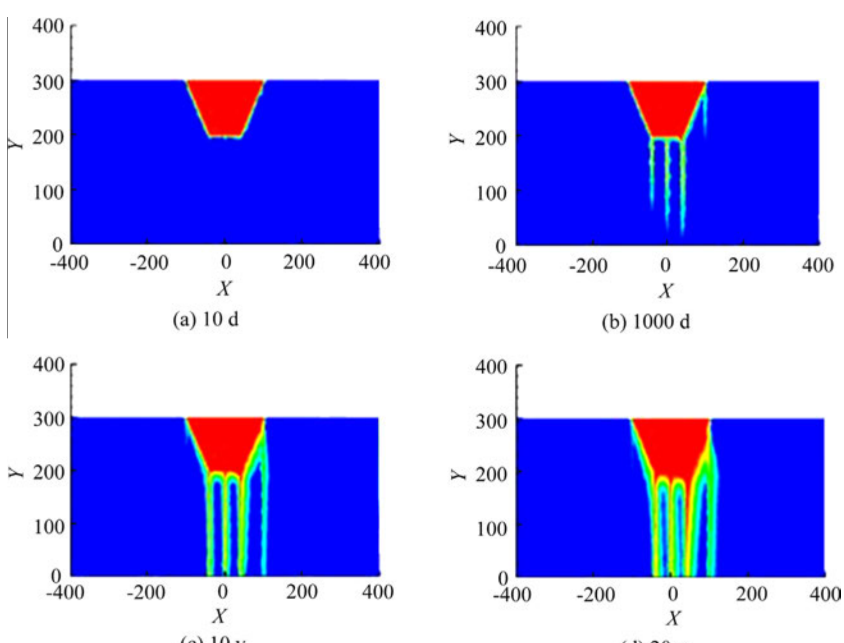

Fig. 9. Simulated contaminant concentration values at 10 days, 1000 days, 10 years and 20 years in open pit filled with waste rocks in a rock mass with vertical fractures (Case 2).

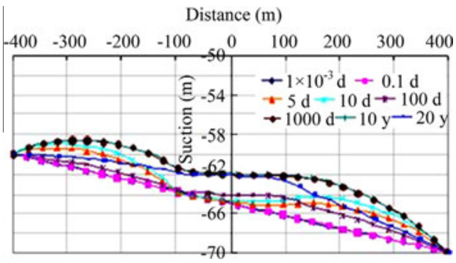

Fig. 11. Simulated pore water pressures (suction head) at $y = 280$ m in open pit filled with waste rocks in a rock mass with orthogonal fracture network (Case 3).

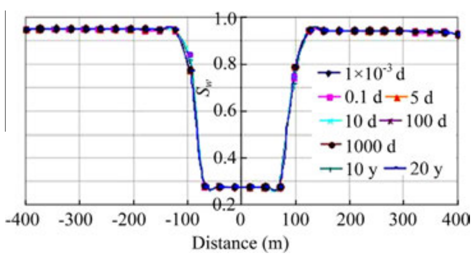

Fig. 12. Simulated saturation degree values at $y = 280$ m in open pit filled with waste rocks in a rock mass with orthogonal fracture network (Case 3).

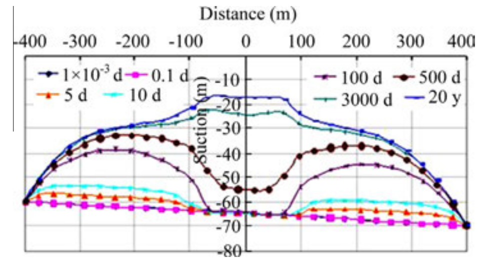

Fig. 14. Simulated pore water pressures (head suction) at $y = 280$ m in open pit filled with tailings in a homogeneous rock mass (Case 4).

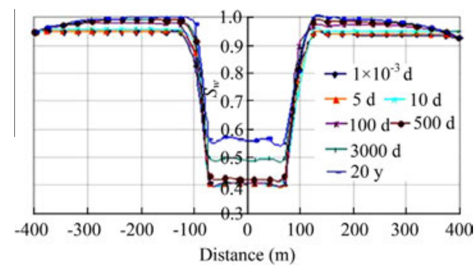

Fig. 15. Simulated saturation degree values at $y = 280$ m in open pit filled with tailings in a homogeneous rock mass (Case 4).

same initial and boundary conditions in the open pit filled with waste rocks are applied here.

Case 4: homogeneous rock mass in open pit filled with tailings

The rock mass is homogeneous in Case 4. Figs. 14 and 15 represent the simulated distributions of the suction and saturation degree as a function of time and distance along a horizontal section located at $y = 280$ m. From these figures, it can be observed that the variations are more pronounced compared with Case 1. Fig. 14 shows that the suction decrease in the tailings is quite significant over time. Fig. 15 shows a major increase in the saturation degree of the tailings over time. Such a progressive increase could help reduce the oxidation of reactive minerals and AMD production [2], where S_w exceeds about 85% in the long term.

The evolution of contaminant concentrations with time is shown in Fig. 16. It can be seen that, in comparison with the pit filled with waste rocks (Case 1), the lateral migration is somewhat more remarkable here, with the plume oriented slightly along the direction of the regional gradient.

Case 5: rock mass with orthogonal fractures in open pit filled with tailings

In Case 5, introducing an orthogonal fracture network with 0.3 mm aperture (Fig. 10) leads to the results shown in Fig. 17.

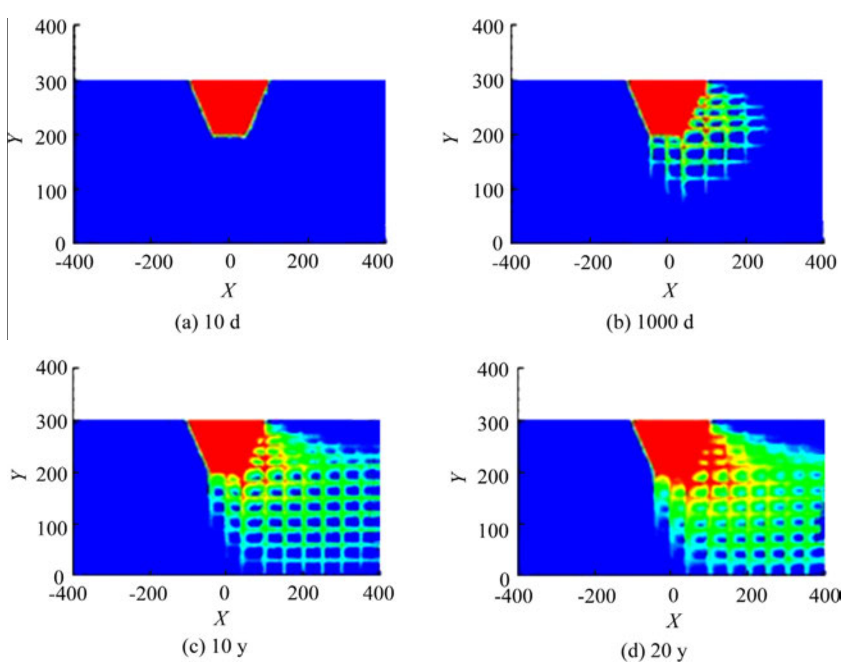

Fig. 13. Simulated contaminant concentration values at 10 days, 1000 days, 10 years and 20 years in open pit filled with waste rocks in a rock mass with orthogonal fractures (Case 3).

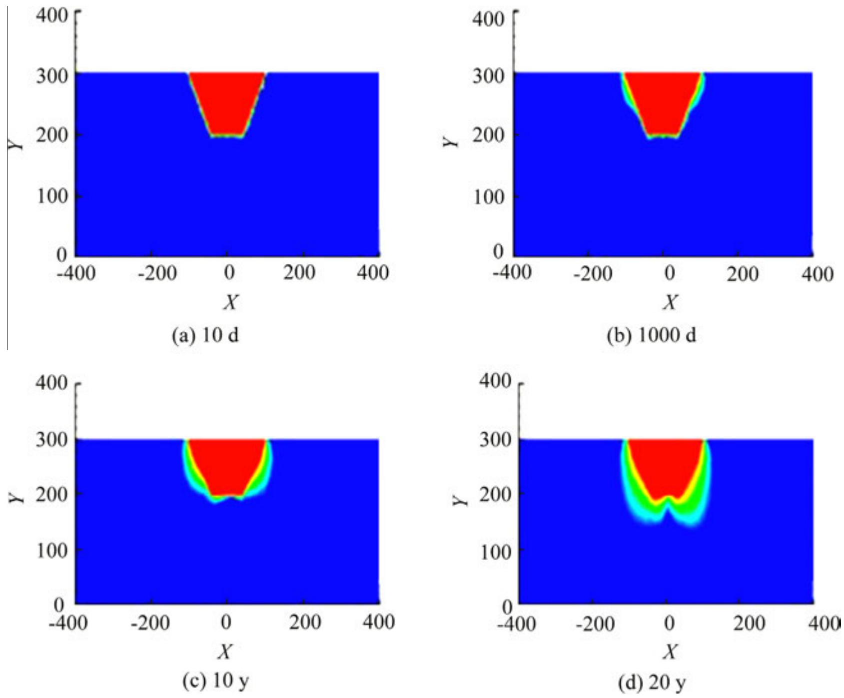

Fig. 16. Simulated contaminant concentration values at 10 days, 1000 days, 10 years and 20 years in open pit filled with tailings in a homogeneous rock mass (Case 4).

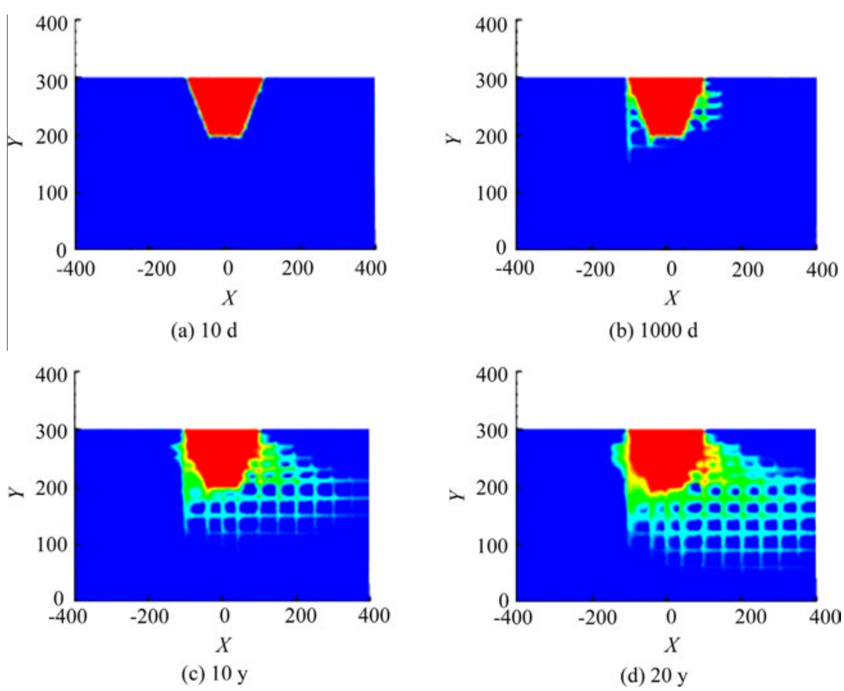

Fig. 17. Simulated contaminant concentration values in open pit filled with tailings in a rock mass with orthogonal fracture network (Case 5).

The fractures have a great influence on contaminants transport for the open pit filled with tailings. Fig. 17 indicates that contaminants migrate rapidly through the fractures, thus much greater distances is reached than the homogeneous rock mass. In comparison to Case 3 (i.e., the open pit filled with waste rocks composed of orthogonal fracture network), the extent of the contaminants migration plume is smaller here.

Table 3 lists the values of simulated contaminant concentrations for both filling materials after 20 years at two observation wells located at $x = 150$ m and 200 m with the elevation y equal to 200 m. The results in Table 3 indicate that the concentrations are higher in the waste rocks when the rock mass is fractured. For both two filling materials, as expected, the concentrations are larger in the first observation well located closer to the pit.

Case 6: effect of a variable recharge rate

In Case 6, the recharge rate on the surface of actual site varies with time. Data from the Latulipe meteorological station, located in the North-West of the Québec province, Canada, was used to provide a more realistic recharge rate. As can be seen from Fig. 18, the precipitation starts at day 120 (end of the cold winter),

Table 3
Simulated contaminant concentrations after 20 years for cases with orthogonally fractured rock mass (kg/m^3).

Type of filling material	Observation well 1 (x = 150 m)	Observation well 2 (x = 200 m)
Waste rocks	0.92	0.82
Tailings	0.73	0.57

then the maximum is reached at day 273 and the precipitation ends on day 303 (start of winter). The somewhat simplified cyclic recharge was considered in this simulation, i.e., with 1 day of precipitation followed by 2 days without precipitation for each month in the total simulated time of 20 years.

For this simulation, the fixed water table was positioned at an elevation of 50 m (i.e., 150 m from the base of the pit). Hydraulic heads of 50 m and 40 m were specified for the left and the right boundaries, respectively, thus the hydraulic gradient occurred. The decreasing head between 50 m and 40 m was also assigned at the base of the model (y = 0 m) with x varying between −400 m and +400 m. The pit is filled with tailings, while the rock mass is considered homogeneous.

Changes of pressure and saturation degree with time obtained along the line located at y = 280 m are provided in Figs. 19 and 20. It can be noticed that the pressure increased with time both in the rock mass and tailings. Fig. 19 shows that, after 20 years, the pressure become positive values in the open pit, which corresponds to the full saturation of tailings (Fig. 20). This progressive saturation of the open pit can be beneficial to control oxygen migration through the tailings and the related geochemical reactions that can produce contaminated acid mine drainage [2].

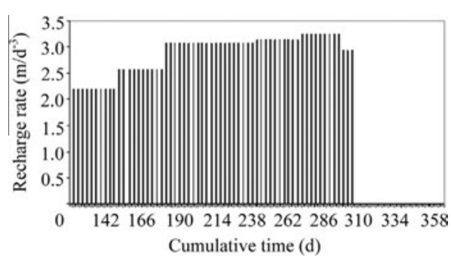

Fig. 18. Precipitation distribution with time.

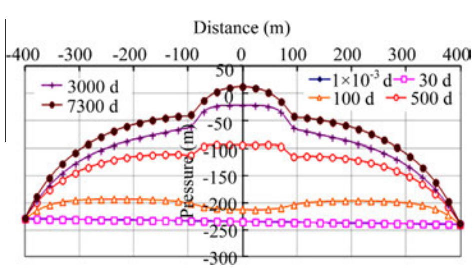

Fig. 19. Simulated pore water pressures (head suction) at y = 280 m in open pit filled with tailings in the case of a variable recharge rate (Case 5).

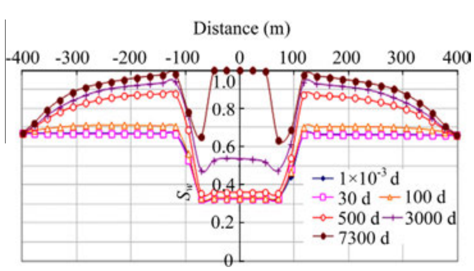

Fig. 20. Simulated saturation degree values at y = 280 m in open pit filled with tailings in the case of a variable recharge rate (Case 5).

6. Discussion and conclusions

Numerical simulations of the unsaturated water flow and contaminants transport through mining wastes stored in an open pit within a fractured rock mass are presented and discussed. These simulations were conducted with the 3D numerical code and Hydro-Geosphere. Main factors which affect water flow and contaminants plume from mine wastes were highlighted in this paper. Obtained results show that:

(1) Unsaturated water flow and contaminants transport are affected by the open pit filling material, the presence of fracture in the rock mass and the imposed initial and boundary conditions.
(2) For the homogeneous (non-fractured) rock mass, water tends to accumulate in the open pit due to recharge and infiltration. This induces the decrease of the pore water pressure head (suction) with time and the increase of the saturation degree with time within the open pit. The rock mass remains at high saturation due to its high air entry value.
(3) With orthogonal fracture network introduced into the rock mass, the saturation degree variation is limited in time and moisture does not tend to accumulate in the open pit. This is due to the fact that water could not accumulate and that fractures are preferential water flow pathways.
(4) Contaminant plume is more affected by the regional gradient under the condition of the presence of orthogonal fracture network. The degree of fractures is an important factor in the evaluation of contaminants transport in fractured rock mass.
(5) Contaminant concentrations are higher for an open pit filled with wastes rock than with tailings. Thus it can be supposed that tailings present less risk for pollution and less environmental impact.
(6) More realistic seasonally varying recharge rates of precipitation may affect the pressure and saturation degree of the wastes located in the pit. Thus actual and representative climatic data should be used to analyse specific cases.
(7) Hydro-Geosphere is a powerful numerical tool which has the advantage of rapid convergence and complex problems resolution.

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