International Research Journal of Earth Sciences ISSN 2321–2527
Vol. **3(1),** 38-45, January **(2015)** *Int. Res. J. Earth Sci.*

Numerical analysis of Unsaturated water Flow and contaminants Transport Around mining Wastes disposed in a Fractured rock Mass

Ben Abdelghani F.
Department of Civil Engineering, Institut Supérieur de technologies de l'Environnement, de l'Urbanisme et de Bâtiments, Tunis 2035, TUNISIA
Research Institute on Mines and the Environment (RIME), Polytechnique Montréal, Montréal, Québec H3C 3A7, CANADA

Available online at: www.isca.in, www.isca.me
Received 13th December 2014, revised 2nd January 2015, accepted 20th January 2015

Abstract

Numerical simulations of water flow and mass transport were carried out to investigate the influence of discontinuities in the rock mass on underground water flow around an open pit filled with mining wastes. Simulations were conducted using the HydroGeosphere numerical tool. The analyses were realized by considering 2D cases for an axi- symmetric open pit under unsaturated water flow conditions. The obtained experimental material properties were used for various 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 many factors can affect unsaturated water flow and contaminants transport ,especially the filling material, the initial and boundary imposed conditions and the fracture network. Presence of fractures can induce a more rapid migration of contaminants and contamination plume can reach more important distances which can increase underground water contamination risk. So, fractures around the rock mass must be characterized and discretely presented to better estimate the contamination plume.

Keywords: Water flow, contaminants migration, tailings, waste rocks, hydro geosphere, numerical modeling, fractures.

Introduction

In Quebec, Canada, over than 100 million tons of wastes are produced each year by mining operations which are usually disposed of in surface facility[1,2]. Produced residual materials made of waste rocks or tailings can be placed in open pits or in underground stopes. Each type of waste can be specifically manage according to its properties, to the mine operating system and the site specifications. Mine dimensions are different from site to another. Depending on treated material characteristics, the effect on environment are different[2]. Recently, mining industry, government and research groups are oriented to develop tools and geo-environmental methods to better manage mining liquid and solid wastes, and are focused to find better rehabilitation strategies. Waste rocks, extracted from underground to reach mineralized zones, are coarse materials with graded granulometry containing particles size of sand and gravels. These are usually disposed at the surface as waste rock piles[3]. Tailings, whereas, are commonly produced as a pulp with density ranging from 30 to 45 % w/w of solids, which can reach more than 80 % in case of pulp residue[2,4]. We store them in ponds called mining wastes stockpiles, which are usually surrounded by an embankment (depending on location topography) and their bottom can be impervious. This technique of disposal can induce some problems, especially for residue embankment geotechnical stability.

Water flow through mining wastes can produce a contaminated leachate, formed by an acid mine drainage (AMD). AMD process, which affects many mining operations over the world, takes place when mining wastes are containing sulfidic minerals (ex. pyrite, pyrrhotite, etc.) which oxidize in presence of water and oxygen[2]. In order to ovoid or to minimize contaminants transfer associated with AMD, it is beneficial to isolate hydraulically these wastes. This is particular possible, in some cases, when mining wastes are disposed into open pits[5]. This is last alternative is analyzed here. In our simulations, we consider that mining wastes are a potential contamination source when they are disposed into a fractured rock mass (a contamination concentration equals to unity will be considered for transport simulation). If fracture network is sufficiently permeable and interconnected, water flow and contaminants transport can be significants[6]. To evaluate solute mobility in this particular field is an important challenge. Mining wastes disposal in an open pit is a recommended technique when wastes are less permeable than the surrounding fractured rock mass[5]. Under these conditions, a great quantity of a regional water flow tend to get around naturally the pit (and wastes). When contaminated mining wastes, in contact with a fractured rock mass, are relatively pervious, contaminants could spread in the different components of the rock mass, i.e the intact rock mass, fractures and fractures network. Significant contributions to better understand water flow and solute transport in fractured porous medium were presented recently, especially to find solutions and new alternatives for radioactive wastes disposal [7,8,9].

In this paper, Hydro Geosphere[10], a 3D finite element code, were used for all conducted simulations. Two different cases with two types of filling material were considered and results are presented and discussed. The effect of an orthogonal fracture network is also considered.

Methodology

Water flow in a porous medium: In a non fractured medium, the unsaturated water flow equation is obtained using the Navier-Stockes equation, continuity equation and Darcy's law. This equation can be written as follows [11,12]:

$$\frac{\partial}{\partial x}\left(k_x(\psi)\frac{\partial \psi}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(\psi)\frac{\partial \psi}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z(\psi)\frac{\partial \psi}{\partial z}\right)+\frac{\partial k_z(\psi)}{\partial z}=-\frac{\partial \theta}{\partial t} \tag{1}$$

Where: kx, ky and kz are the components of hydraulic conductivity tensor (m/s), respectively in the x, y and z direction; Ψ is the suction (negative pressure) (m) and Θ is the water content (-)

Water flow in a single fracture: Water flow in a single fracture is described by the called cubic law which is an analytical solution of the Navier-Stokes equation for laminar and steady state water flow. In this law, a single fracture is assimilated to two planar surfaces. This law can be written as follow [13,14]:

$$Q_f = V_f \times A_{\text{sec}} = -\left(\rho_w g b^3 \omega \Delta h\right)/12\mu_w L) \tag{2}$$

$$Asec = bxw \tag{3}$$

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).

To take into account the influence of additional parameters, such as surface roughness, tortuosity, and Reynolds number, Equation[2] can be modified[15,16].

For transient and partially saturated water flow conditions, Equation-2 can be used to determine the continuity equation of flow discharge and the equation of partially saturated water flow in fractures [17]. Under these conditions, the unsaturated hydraulic functions of the materials and fractures must be defined.

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[9]:

$$\left[\frac{\partial}{\partial x}\left[\left(\frac{\rho g e^3}{12\mu}\right)k_{rx}(\Psi)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[\left(\frac{\rho g e^3}{12\mu}\right)k_{ry}(\Psi)\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[\left(\frac{\rho g e^3}{12\mu}\right)k_{rz}(\Psi)\frac{\partial h}{\partial z}\right]\right]=\frac{\partial \theta_f(\Psi)}{\partial t} \tag{4}$$

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.

Contaminants transport: Contaminants migration through fractured rock mass can be greatly affected by presence of fractures. Do to the to the complexity of fracture network and the significant role of fractures on affecting contaminants migration, this aspect is difficult to consider and to evaluate. For non reactive contaminants, the main transport modes are advection and hydrodynamic dispersion. Advection controls the migration by water flow in response to an hydraulic gradient. More the hydraulic gradient is significant, more the migration velocity is important. Hydrodynamic dispersion includes molecular diffusion which induces contaminants transport in response to a concentration gradient (movement from medium with high concentration to another with less concentration) and mechanical dispersion is caused by local variations of water velocity and tortuosity of water pathways.

Three-dimensional transport in a variably-saturated porous matrix is described by the following equation [10]:

$$\Theta_s S_w R\frac{\partial c}{\partial t}+q_i\frac{\partial c}{\partial x_i}-\frac{\partial}{\partial x_i}\left[\Theta_s S_w D_{ij}\frac{\partial c}{\partial x_j}\right]+\Theta_s S_w R\lambda c=0 \tag{5}$$

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 [11] :

$$R = 1+\frac{\rho_b}{\Theta_s S_w}K_d \tag{6}$$

où ρ_b est le poids volumique du milieu granulaire (en g/cm^3), et K_d est le coefficient de distribution du contaminant. Le coefficient de dispersion hydrodynamique D_{ij} (en m^2/s) est donné par [10] :

$$\Theta_s S_w D_{ij} = (\alpha_L-\alpha_T)\frac{q_i q_j}{|q|}+\alpha_T|q|\delta_{ij}+\Theta_s S_w \tau D_d \delta_{ij} \tag{7}$$

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 (without unit) [-]; 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. The tortuosity coefficient usually varies between 0.01 and 0.5[11]. Mechanical dispersion in the fractures and the matrix is described by longitudinal and transverse dispersivities. HydroGeosphere accounts for a horizontal and a vertical component of the transverse dispersivity in the 3D porous medium. Other equations similar to equations (4) and (6) can be written to describe contaminant transport in the variably-saturated fracture.

The Hydro Geosphere code: The numerical tool HydroGeosphere was used here to undergo numerical simulations presented in this paper[10]. It's a 3D model based on space discretization where water flow and contaminants transport are studied. The model resolves water flow equations for surface/underground flow coupled with contaminants transport in discretely-fractured. It is a model based on control volume finite element method which allows subsurface saturated or unsaturated water flow, coupled to mass transport by advection-dispersion in the porous media (non fractured). The HydroGeosphere model simulates also water flow and contaminants transport in 2D fracture elements. Variably-saturated flow is described by a modified form of Richards' equation where the storage term is expanded to consider water and soil compressibility[9]. 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. For transient flow, simulation period time is discretized into time steps. A finite element algorithm resolves a matrix system formed by water flow equations for all mesh nodes. Final solution obtained by the Hydro Geosphere code can be hydraulic head value at each node, the components of mean velocity at the middle of each element and the mean value of flow rate. For non saturated conditions, the mean degree of saturation is also a part of the final solution. Retention and relative permeability curves for both the fractures and the matrix can be expressed from van Genuchten's Function or can be specified in a tabular form[18]. In the model, the porous medium is discretized with 3D finite elements whereas fractures are discretized with 2D finite elements. It is assumed that there is continuity of hydraulic head and concentration in the fracture and matrix at 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. 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.

Results and Discussion

Open pit conceptual model: Figure-1 presents the 2D conceptual model of an open pit filled with mining wastes obtained with the Hydro Geosphere code. The open pit is axisymmetric with a depth of 150 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 x axis of the model is from 0 to + 400 m. This right boundary is chosen far from x = 0 to avoid influence on model response. Two types of filling material are considered: waste rocks from extraction operations and tailings obtained from mineralogical treatment process. As mentioned previously, waste rocks are characterized by a very graded granulometry with especially sand and gravel particle sizes, whereas, tailings have a granulometry dominated by silty and sandy fractions (Aubertin and al., 2002).

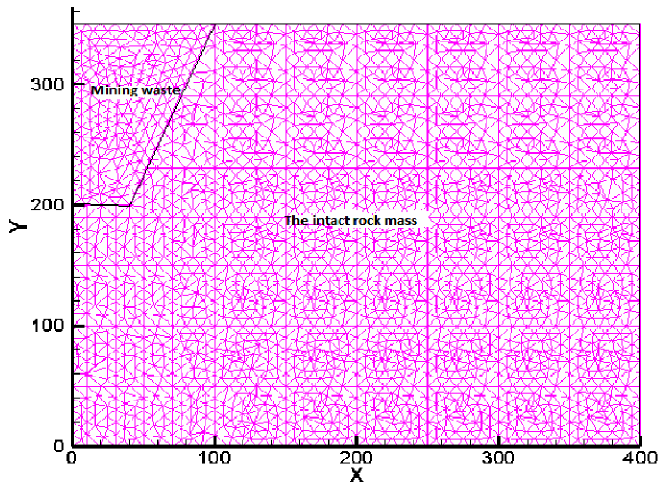

Figure-1
Conceptual model of an axisymmetric open pit with grid mesh (not to scale)

Material hydrogeological characteristics: Waste rocks and tailings particle size distribution can affect their hydrogeological properties, as the hydraulic conductivity and water retention curve. Saturated hydraulic conductivity values of waste rocks can vary greatly with materials texture[3]. Their air entry value (pressure head) is low because these coarse materials can desaturate easly under low suction values. Whereas, tailings which are initially high saturated have a saturated hydraulic conductivity relatively low, and they can retain water by capillarity under unsaturated conditions of water flow[2].

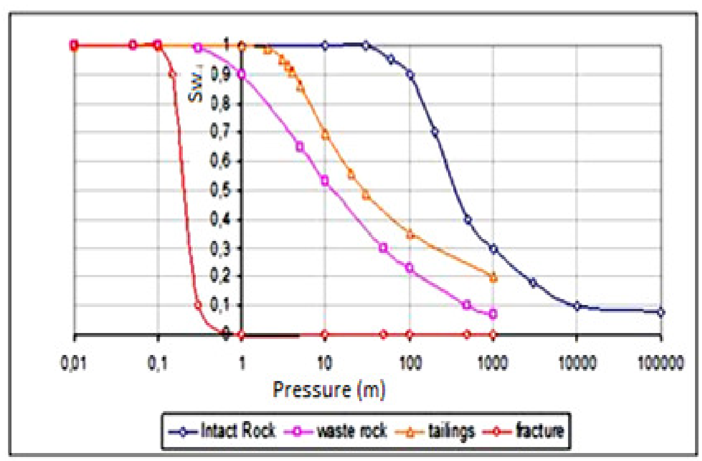

Figure-2
Water retention curves for the different materials

Water retention curves, as shown in figure-2, represent the variation of the saturation degree versus pressure for the tailings, the waste rocks, the intact rock (porous media) and the fractures. Hydric functions for different materials were extracted using representative experimental data from Aubertin and al. for waste rocks, from Cifuentes (2005) for tailings and from Wang et Narasimhan (1985) for the rock matrix[3,8,19].

Table-1 lists the corresponding hydrogeological parameters for the various materials based on the van Genuchten equations[18].

For all conducted simulations, the initial water table is located at the elevation of 200 m (i.e., at the base of the pit) so an hydraulic head of 200 m was imposed at the base of the model (for y = 0 m). This implies that mining wastes are initially unsaturated. The model axis (at x = 0 m) is an impervious boundary because of the radial symmetric revolution. The vertical right boundary located at x = 400 m and the base of the model are considered impervious for water flow. A constant recharge rate of 1.5 mm/d is imposed 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.

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

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

Parameter	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

Open pit filled with waste rocks: All simulations were conducted under unsaturated conditions and transient flow. The Gridbuilder code V.5.6 (McLaren, 2005) was used to generate mesh grid and the Tecplot package was used for results extraction[20]. This simulation has generated 8128 nodes and 7906 elements. Two different cases are presented and discussed: a first case with an homogeneous rock mass (without fractures) and a second case with a fractured rock mass (an orthogonal fracture network is added).

Case of an homogeneous rock mass: Figures-3 and -4 shows the simulated results expressed as water pressure and saturation degree variations as a function of time and elevation along a vertical axis located at x = 40 m for a non-fractured rock mass. Figure-3 shows a linear variation of pressure with elevation and an increasing of pressure values with simulation time due to precipitation and water infiltration. Also, as shown in figure- 4, the saturation degree increases in the open pit due to its filling over time. Initially, waste rocks remain at low values of saturation (i.e Sw ~ 22 %), which is near of their saturation residual value. We can also notice that the saturation degree increases in the mining wastes with time due to regional water flow.

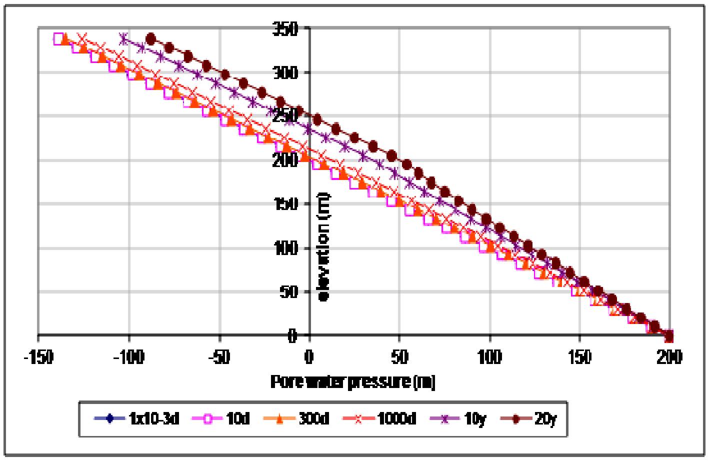

Figure-3
Simulated Pore water pressure head at x = 40 m in open pit filled with waste rocks in a homogeneous (non fractured) rock mass

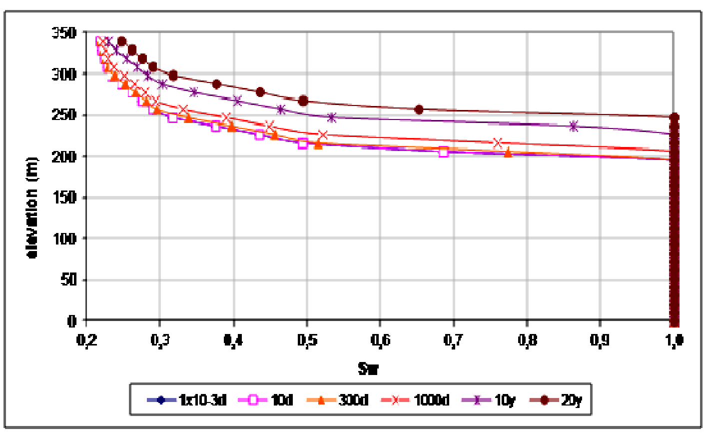

Figure-4
Simulated values of the saturation degree at x = 40 m in open pit filled with waste rocks in a homogeneous (non fractured) rock mass

Figure-5 shows the obtained results of contaminant concentration levels at 10 days, 300 days, 1000 days and 20 years. This figure shows that the concentration remains constant (unity) inside the open pit (imposed condition) and there is a contaminant migration with time, with depth and laterally to the pervious boundary located at x = 400 m. Laterally contaminant migration is quite slow, but it progresses over time and with depth due to precipitation effect. The low hydraulic conductivity value of the rock mass (non fractured) restricts the contaminants plume extent.

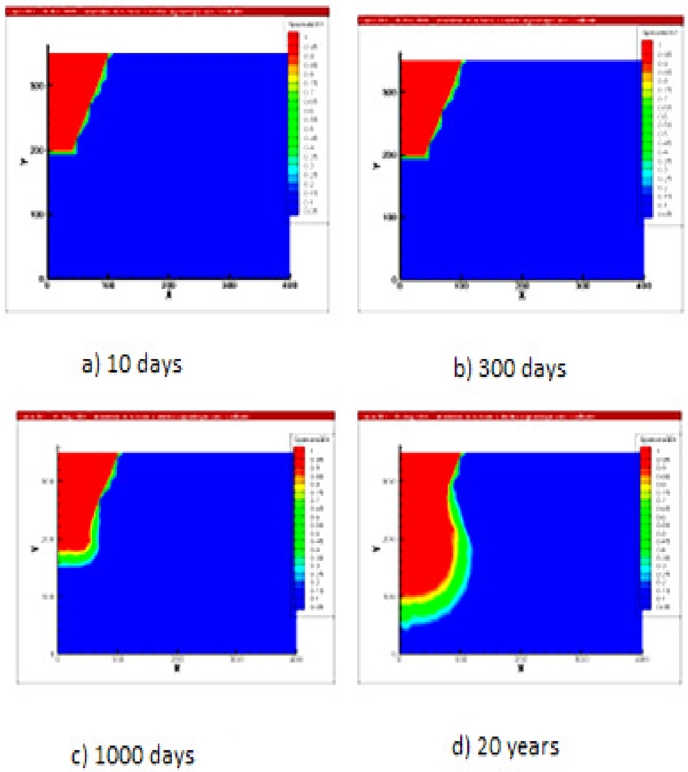

Figure-5
Simulated contaminant concentration values at 10 days, 300 days, 1000 days and 20 years in open pit filled with waste rocks in a homogeneous rock mass

Effect of an orthogonal fracture network: In this second simulation, an orthogonal fracture network is introduced into the rock mass. The vertical fractures are located at x = 40 m, 100 m, 150 m, 200 m, 250 m, 300 m and 350 m. 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 et 290 m. All fractures have the same and a constant aperture of 0.3 mm. Results of pore water pressure and saturation degree variations with time and elevation (not shown here) indicated fractures effect on system desaturation. In fact, due to the hydraulic conductivity contrast between fractures and rock mass, water flows rapidly with fractures, which causes the desaturation.

Results relative to contaminants migration with time (concentration levels at 10 days, 300 days, 1000 days and 20 years) are illustrated by figure-6. This figure shows a significant difference in contaminants plume in comparison with the case of an homogeneous rock mass (see figure- 5). Here, we note that contaminants migration is more pronounced and is occured especially through the fracture networks. Contaminants outlet is also more important here and mainly progresses downward and laterally. But, since the vertical boundary is impervious, lateral migration is low over time.

Open pit filled with tailings: Case of an homogeneous rock mass: Here, the open pit is filled with tailings which have a saturated hydraulic conductivity much lower than for waste rocks, but nearly of the intact rock mass. The same initial and boundary conditions in the open pit filled with waste rocks are imposed here. The rock mass around the pit is homogeneous (no fractures, see figure-1). Results of simulated distributions of pore water pressure and saturation degree (S_w) as time and elevation with a vertical section located at x = 40 m are shown in figures- 7 and 8. According to these figures, the variations are more important in tailings than the rock mass. In fact, the rock mass remains saturated to an elevation of 200 m, whereas S_w varies between 32 % and 100 % in tailings. There is an increase in water content values with time in the open pit caused by water table ascent and progressive filling of the pit.

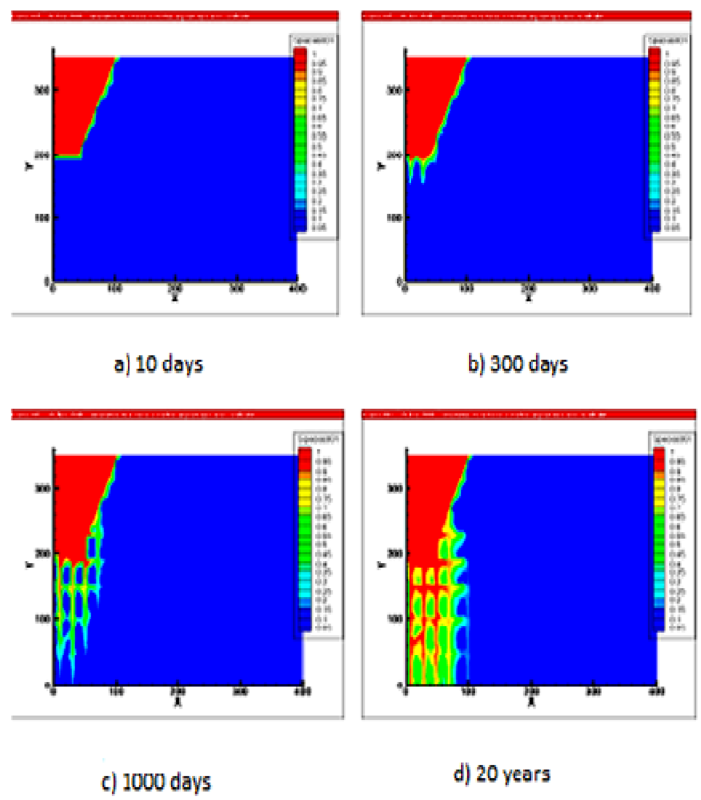

Figure-6
Simulated contaminant concentration values at 10 days, 300 days, 1000 days and 20 years in open pit filled with waste rocks in a fractured rock mass

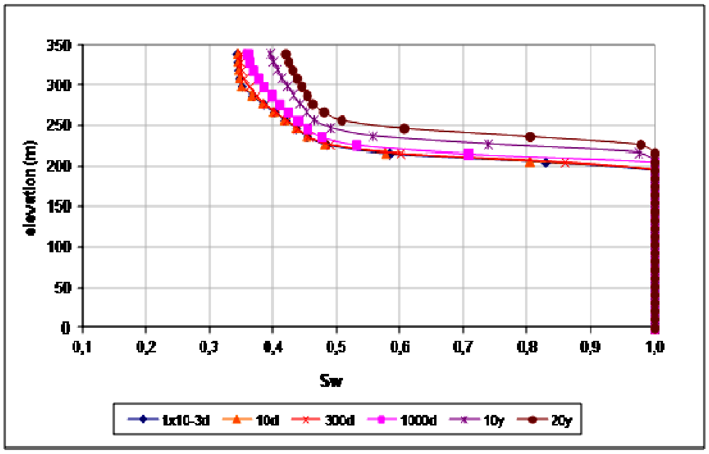

Figure-7
Simulated values of the saturation degree at x = 40 m in open pit filled with tailings in a homogeneous (non fractured) rock mass

The evolution of contaminants concentration with time is shown in figure- 9. This figure displays a low contaminants migration over time. In comparison with obtained results in figure-5, contaminants migration is less significant for tailings. So, we can suppose that tailings present less contamination risk than waste rocks.

Fractured rock mass: In this case, introducing an orthogonal fracture network with 0.3 mm aperture leads to the results of contaminants migration shown in figure-10. These results confirm those of open pit with waste rocks. The fractures have a great influence on contaminants migration. However, contaminants migration is less significant here than for open pit with waste rocks around fracture rock mass. Also, lateral migration is still limited over time due to the impervious boundary.

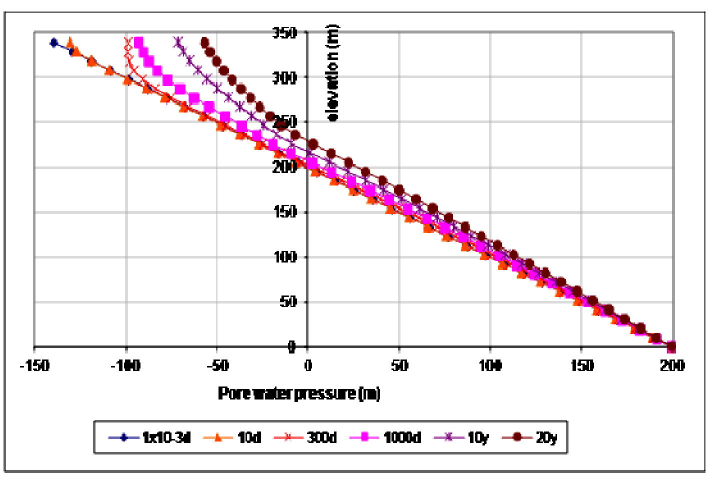

Figure-8
Simulated Pore water pressure head at x = 40 m in open pit filled with tailings in a homogeneous (non fractured) rock mass

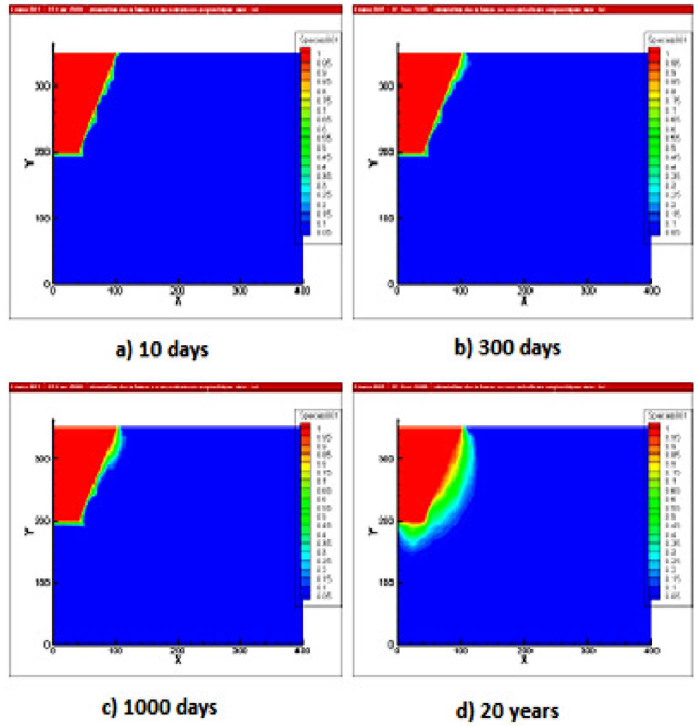

Figure-9
Simulated contaminant concentration values at 10 days, 300 days, 1000 days and 20 years in open pit filled with tailings in an homogeneous rock mass

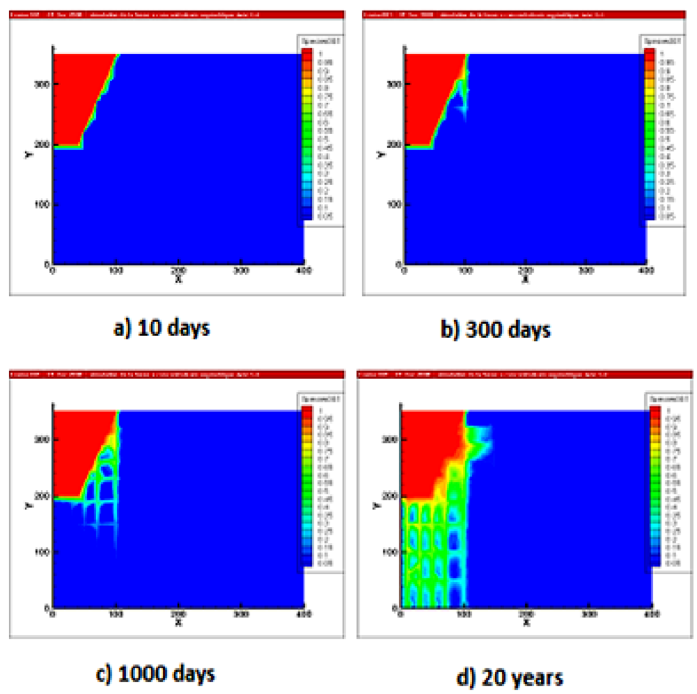

Figure-10
Simulated contaminant concentration values at 10 days, 300 days, 1000 days and 20 years in open pit filled with tailings in a fractured rock mass

Conclusion

This numerical study conducted with the 3D numerical code called HydroGepshere highlights that many factors may affect unsaturated water flow and contaminants transport through mining wastes when they are stored in an ax symmetric open pit. The obtained results show that:

Unsaturated water flow and contaminants transport are essentially affected by the open pit filling material, the imposed initial and boundary conditions and the presence of fractures in the surrounding rock mass.

For the homogeneous (non-fractured) rock mass, water tends to accumulate in the open pit due to recharge and infiltration. This induces the increase of the pore water pressure with time and of the saturation degree in the open pit

With an 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. The pore water pressure and saturation degree distributions with time and elevation become less significant.

When fractures are present, they can affect contaminants transport. In fact, contaminants could migrate more rapidly and could reach more important depth and distances from source which can increase contamination risk. Rock mass fracturation degree is an important factor to be considered to correctly evaluate contaminants transport through mining wastes.

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.

HydroGeosphere is a powerful numerical tool which has the advantage of rapid convergence and complex problems resolution.

Acknowledgment

The authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the partners of Research Institute on Mines and the Environment (RIME UQAT-Polytechnique).

References

1. Aubertin M., Bussière B. and B. Zagury, *La gestion des rejets miniers au Québec*, L'État du Québec 2011, Institut du Nouveau Monde, Boréal, 225-232 **(2011)**
2. Aubertin M., Bussière B. and L. Bernier, *Environnement et gestion des rejets miniers*, Presses Internationales Polytechniques, Manuel sur CD-Rom **(2002)**
3. Aubertin M., Fala O., Molson J., Rochette A.G., Lahmira B., Martin V., Lefebvre R., Bussière B. and Chapuis R.P., Chouteau M. and W.G. Wilson Évaluation du comportement hydrogéologique et géochimique des haldes à stériles. *Symposium Rouyn-Noranda: l'Environnement et les Mines*, Rouyn-Noranda, Canada, CIM, Compte-rendus sur CD-Rom **(2005)**
4. Martin V., Aubertin M. and J. McMullen Surface disposal of paste tailings. *Proc. 5th ICEG Environmental Geotechnics*: *Opportunities, Challenges and Responsibilities for Environmental Geotechnics*, Thomas H.R. (ed.), Cardiff UK, **2**, 1471-1478 **(2006)**
5. Thériault V., *Étude de l'écoulement autour d'une fosse remblayée par une approche de fracturation discrète.* Master Génie minéral, École Polytechnique de Montréal, Canada **(2004)**
6. Xu J. et B.X. Hu, Stochastic analysis of contaminant transport through non stationary fractured porous media: a dual-permeability approach, *Water Resources Research*, **41**, 13p **(2005)**
7. Schwartz F., Smith L.W. and S.A. Crowe, A stochastic analysis of macroscopic dispersion in fractured media, *Water Resources Research*, **19**, 1253-1265 **(1983)**
8. Wang J.S.Y. and T.N. Narasimhan, Hydrologic mechanisms governing fluid flow in a partially saturated, fractured, porous medium, *Water Resources Research,* **21**, 1861-1874 **(1985)**
9. Therrien R. and E.A. Sudicky, Three dimensional analysis of variably saturated flow and solute transport in discretely fractured porous media, *Journal of Contaminant Hydrology*, **23**, 1- 44 **(1996)**
10. Therrien R., HydroGeosphere, A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport, *Draft eds,* 252 **(2005)**
11. Freeze R.A et J.A. Cherry, *Groundwater,* Prentice-Hall, Inc., Englewood Cliffs, N.J., 604 **(1979)**
12. Freeze R.A. et P.A. Witherspoon, Theoretical analysis of regional groundwater flow: analytical and numerical solutions to the mathematical model, *Water Resources Research*, **2**, 641-656 **(1966)**
13. Witherspoon P.A., Tsang W.Y., Long S.C.J. and J. Noorishad, New approaches to problems of fluid flow in fractured rock masses, *Proceedings of the 22nd US Symposium on Rock Mechanics, Rock Mechanics from research to application, Massachusetts,* June 28-July, **2**, 3-22 **(1981)**

14. Tsang W.Y. The effect of tortuosity on fluid flow through a single fracture, *Water Resources Research*, **20**, 1209-1215 **(1984)**

15. Gale J. Hydraulic behaviour of rock joints", *Proceedings of the International Symposium on Rock Joints*, Balkema, Rotterdam. Barton and Stephansson Eds., 351-362 **(1990)**

16. Indraratna B. and P. Ranjith, *Hydromechanical aspects and unsaturated flow in jointed rock,* A.A. Balkema, 286 **(2001)**

17. Wang J.S.Y. and T.N. Narasimhan, Unsaturated flow in fractured porous media*, Flow and Contaminant Transport in fractured rock,* San Diego, Academic Press, Inc. 169-236 **(1993)**

18. Van Genuchten, M.Th., A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal*, **44**, 892–898 **(1980)**

19. Cifuentes E., *Modélisation numérique des écoulements non saturés dans les couvertures à effets de barrière capillaire inclinées*, Master Génie minéral, École Polytechnique de Montréal **(2005)**

20. Amtec Engineering Inc., *Tecplot,* Version 10, États-Unis Amtec Enginneering Inc., Fichier informatique sur CD-Rom **(2003)**