Use of The HydroGeosphere code to simulate Water flow and contaminants transport around mining waste disposed into an open pit within fractured rock mass.

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Résumé:

Le modèle numérique, HydroGeosphere, a été utilisé afin de simuler l’écoulement de l’eau souterraine et le transport de contaminants autour de rejets miniers entreposés dans un massif rocheux fracturé. Les simulations en 2D incluent la zone vadoze (non saturée) et utilisent les propriétés des matériaux obtenues expérimentalement, pour différentes conditions aux limites. Les effets des propriétés hydrogéologiques des matériaux (c.a.d la courbe de rétention d’eau et la fonction de conductivité hydraulique), des caractéristiques du réseau de fractures, et de la conductivité des joints ont été étudiés. Les résultats des simulations montrent que l’écoulement de l’eau et le transport de contaminants sont grandement affectés par la nature des conditions initiales et aux limites imposées et la fracturation du massif rocheux avoisinant.

Abstract:

A 3D numerical model, called HydroGeosphere, was used to simulate water flow and transport of contaminants around mining waste disposed into an open pit within fractured rock mass. Numerical simulations have been carried out to assess influence of various factors on flow network in and around surface mine openings including surface rainfall, filling material and presence of fractures. The effect of regional hydraulic gradient was also investigated. A parametric analysis was conducted by simulating various 2D cases using experimentally obtained material properties and controlled boundary conditions. The effects of filling material hydraulic properties (i.e. water retention curve and hydraulic conductivity function), fracture network characteristics and saturated hydraulic conductivity of joints are investigated. Numerical simulations illustrate how fractures control water flow and contaminants transport around waste disposal areas. Results highlight the importance of considering a discrete fracture network.

Key-words: HydroGeosphere, open pit, mining waste, waste rock, tailings, modelling, contaminants transport, unsaturated water flow
1. Governing equations

1.1 Water flow in a single fracture
Water flow in fractures is described by the ‘cubic law’ which is an analytical solution of the Navier-Stokes equation for laminar and steady state water flow between two surfaces. It can be expressed as follows [8]:

\[ Q_f = V_f A_{sec} = - \left[ \rho_w g b^3 w \Delta h/12 \mu_w L \right] \]  

(1)

Where:
A_{sec} (= bxw): fracture section (L^2), Q_f: fracture discharge (L^3/T), V_f: mean water flow velocity in fracture (L/T), A_{sec}: area of fracture perpendicular to water flow (L^2), b: fracture aperture (L), w: fracture width transverse to water flow (L), L: fracture length parallel to water flow (L), \Delta h: hydraulic head difference along the flow direction (L), \rho_w: water density (M/L^3), g: gravity acceleration (L^2/T), and \mu_w: water dynamic viscosity (M/L/T). Equation (1) was validated for laminar flow in micro-fractures composed of planar surfaces. Here we neglect surface rugosity.

For transient and partially saturated water flow conditions, Equation (1) can be used with the continuity equation of flow discharge to determine the equation of partially saturated water flow in fractures [7]. Cubic law can be used to obtain water flow expression under unsaturated conditions and transient flow [3].

We note for the rock mass, HydroGeosphere code uses a modified form of Richard's equation for transient flow under unsaturated conditions. This modified equation includes parameter to allow exchange between rock mass and fractures.

1.2 Contaminants transport
Contaminants transport in fractured rock is an important but difficult aspect to consider due to the complexity of fracture networks and the role of fractures affecting contaminant migration. Principal modes of contaminants transport are advection and hydrodynamic dispersion which includes molecular diffusion and mechanical dispersion. Molecular diffusion is often negligible when the porous medium is impervious. In order to describe contaminants transport in a discretely-fractured porous medium, two equations are needed, one for the porous matrix and one for the fractures. Concentration and mass flux continuity at the matrix-fracture interface allow a coupling between equations for fractures and for rock mass.

Three-dimensional transport in a variably-saturated porous matrix is described by the following equation [3]:

\[ \theta S \frac{\partial c}{\partial t} + q_i \frac{\partial c}{\partial x_i} - \frac{\partial}{\partial x_i} \left( \theta S D_s \frac{\partial c}{\partial x_i} \right) + \theta S c = 0 \]  

(2)
in (2) special parameters can be introduced to take into account chemical reactions and contaminant distribution or absorption.

In (2), \( c \) is the concentration (M/L\(^3\)), \( D_{ij} \) is the hydrodynamic dispersion coefficient (L\(^2\)/T), \( q_i \) is the fluid flux (L/T), \( \theta \) is the porosity (-) and \( S_w \) is water saturation (-). The hydrodynamic dispersion coefficient \( D_{ij} \) (L\(^2\)/T), is given by (Bear 1972):

\[
\theta S_w D_0 = (\alpha_l - \alpha_t) \frac{q_i q_j}{|q|} + \alpha_l |q_j| \delta_{ij} + \theta S_w \tau D_0 \delta_{ij} = 0
\]  

(3)

where \( \alpha_l \) and \( \alpha_t \) are the longitudinal and transverse dispersivities, respectively; \( |q| \) is the magnitude of the Darcy flux; \( \zeta \) is the matrix tortuosity; \( D_0 \) is the free solution diffusion coefficient; and \( \delta_{ij} \) is the Kronecker delta. The product \( \zeta D_0 \) represents an effective diffusion coefficient for the matrix (\( D_e \)). Typical values for \( D_e \) under saturated conditions in soils range between 1 x 10\(^{-9}\) and 2 x 10\(^{-9}\) m\(^2\)/s. The tortuosity coefficient usually varies between 0.01 and 0.5 [2].

2. The HydroGeosphere code

The numerical code HydroGeosphere is used for simulations presented here. It is a three dimensional control-volume finite element model that simulates variably-saturated subsurface flow and advective – dispersive mass transport in discretely-fractured porous media. In this numerical tool, fractures are idealized as two-dimensional parallel plates, implying uniform total head and concentration across the fracture width, and flow velocities are determined by the cubic law. In this model, the porous medium is discretized with 3D finite elements. 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 effective diffusion coefficient for solutes in the matrix is given by the product of the free water diffusion coefficient and the tortuosity. All simulations were conducted in 2D for simplification and to be able to use HydroGeosphere results for indirect hydromechanical coupling with Phase\(^2\) code.

3. Conceptual model and material hydraulic characteristics

3.1 Open pit conceptual model

FIG. 1 presents the conceptual 2D model of an open pit filled with mining wastes simulated with HydroGeosphere code. The open pit is symmetric about the axis at x = 0 m. It has a depth of 100 m and the wall slope is 68 ° (from the horizontal axis). The lower limit of the model is 200 m below the pit base. The left and right limits of the model are located respectively at -400 m and +400 m from the origin. Two types of mine material are considered: waste rocks resulting from mining operations and tailings from the milling process. Model grid was created using Grid Builder code, a 2D mesh generator tool. It is a triangular finite element model. This code doesn’t allow us to specify
different element size for different materials but it generates a default mesh which can be refined by user.

3.2 Material hydraulic characteristics

Water retention curves representing the variation of the degree of saturation versus pressure for the waste rocks and intact rock are shown in FIG. 2 (semi–log graph). Table 1 lists hydraulic parameters of various materials. These functions are defined by using experimental data from [1] for mine waste rocks and from [5] for the rock matrix.

3.3 Numerical modelling

For all simulations, initial water table is fixed at 220 m. A regional gradient is generated by imposing a decreasing hydraulic head between 220 m and 210 m at the base of the model for x between – 400 m and + 400 m (which gives a regional gradient of 0.0125). Left and right boundaries are pervious with fixed hydraulic heads of 220 m and 210 m respectively. Across the upper boundary, a constant recharge rate of 1.5 mm/d was assigned for 10 days followed by a period of 10 days without rain in alternation for a period of 20 years. To simulate contaminant migration, a constant unit concentration is fixed within the open pit, and is initially set to zero within the surrounding host rock. The contaminant is assumed inorganic and non reactive with a free diffusion coefficient of \(2 \times 10^{-9} \text{ m}^2/\text{s}\).

FiG. 1- Open pit conceptual model and mesh grid.
All transport model parameters are also summarized in Table 1. Two cases are presented here: a homogeneous rock mass, and a rock mass with an orthogonal fracture network. All simulations are made under unsaturated and transient flow conditions. Tecplot code was used for data extraction and visualization. This simulation has generated 8128 nodes and 7906 elements. The total simulation period was 20 years.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Waste rocks</th>
<th>Intact Rock</th>
<th>Transport parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.34</td>
<td>0.02</td>
<td>Tortuosity $t$</td>
<td>0.1</td>
</tr>
<tr>
<td>Air entry value</td>
<td>0.3 m</td>
<td>35 m</td>
<td>Matrix longitudinal dispersivity</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Ksat (m/s)</td>
<td>$1 \times 10^{-5}$</td>
<td>$3.2 \times 10^{-8}$</td>
<td>Matrix transverse dispersivity</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Residual volumetric water content</td>
<td>0.03</td>
<td>0.0015</td>
<td>Fracture longitudinal dispersivity</td>
<td>0.5 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fracture transverse dispersivity</td>
<td>0.05 m</td>
</tr>
</tbody>
</table>

4 Modelling results and discussion

Case 1: case of homogeneous rock mass

Here, the open pit is filled with waste rocks material. FIG. 3a and 3b show simulated profiles of pressure and degree of saturation as a function of time and distance within a horizontal section at $y = 280$ m. FIG. 4 shows results of contaminants concentration evolution with time. From FIG. 3a, it can be seen that the initial pressure variation is linear with distance and varies between -60 m and -70 m for $x$ varying between -400 m and +400 m. With time and due to precipitation, the pressure increases greatly, especially within the rock mass. Due to the regional gradient, values are more important at the left side of the model than its right side.
FIG. 4 shows that as time increases and due to precipitations effect, migration becomes more significant especially with depth. After 20 years of simulation, contaminants reached a maximum of concentration at a depth of 50 m from the base of the open pit. Due to the low value of the regional gradient, the contaminant outlet is quite symmetric.

FIG. 3- Pressure and saturation profiles along y = 280 m, open pit filled with waste rocks, case of homogeneous rock.

FIG.4- Results of concentration distribution with time; open pit filled with waste rocks, case of homogeneous rock mass.
Case 2: Effect of orthogonal fractures

An orthogonal fracture network is introduced into the rock mass. All fractures have an aperture of 0.3mm (which corresponds to a saturated hydraulic conductivity of about 0.0612 m/s). A total of 11 horizontal fractures and 15 vertical fractures are added to the rock mass. Simulated profiles of suction and degree of saturation as a function of time and distance (not shown here) illustrate the influence of orthogonal fractures on water flow network. In fact, the rapid water flow through fracture network (due to the high hydraulic conductivity) limits pressure variations in comparison to the case with homogenous rock mass. Also, the variation of degree of saturation is very low in both rock mass and waste rocks. We can therefore say that introducing orthogonal fracture network have a desaturation effect. This is due to significant water flow through the fracture network and water hasn’t enough time to accumulate.

FIG. 5 shows that contaminants migration is more important here and there’s a preferential contaminant migration through fracture network. In contrast to case 1 (no fractures), contaminants migrate more rapidly here with the regional gradient. With time, there is an interconnexion between vertical and horizontal fractures. We can also notice that contaminant plume is oriented in the direction of regional gradient. This can increase the risk of groundwater contamination.

![FIG. 5](image_url)

FIG.5- Results of concentration distribution with time; open pit filled with waste rocks, case of rock mass with orthogonal fracture network.
HydroGeosphere code has the possibility to generate a random fracture network. In this case fractures will have different apertures with different lengths and orientations. Considering here an orthogonal fracture network is a simplification.

5 Conclusion

This study highlights that many factors affect water flow and contaminants transport from mine wastes stored in open pits in fractured rock. Basing on simulations conducted with the 3D HydroGeosphere code for a symmetric open pit with effect of a regional gradient, we can conclude that:

- Water flow and contaminants transport are largely affected by the type and nature of initial and boundary conditions and the nature of the rock mass (homogeneous or fractured).
- For a homogeneous rock mass case, water accumulates in the open pit due to water infiltration. For contaminants transport, migration is more significant with depth than laterally. Contaminant plume is not influenced by the regional hydraulic gradient and is keeping symmetric.
- When an orthogonal fracture network is added to the rock mass, water will flow rapidly through fractures and will not have enough time to accumulate. This leads to a certain desaturation of the system. Variations in the pressure and degree of saturation over time become less important than the case of homogeneous rock mass. For Contaminants transport, migration is more important in presence of fractures and contaminants migrate preferentially through fracture network.
- A regional gradient can have a great effect on the water flow network and on contaminants transport. Contaminant concentrations are greater in the direction of the regional gradient. This difference in concentrations becomes more importance with time.
- 3D simulations with introducing a 3D fracture network will be for great interest to approach reality.

References