International Journal of Mining Science and Technology 25 (2015) 37–45

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

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

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ARTICLE INFO

*Article history:*
Received 2 March 2014
Received in revised form 15 May 2014
Accepted 15 July 2014
Available online 4 February 2015

*Keywords:*
Hydro-Geosphere
Numerical modelling
Unsaturated water flow
Contaminants transport
Tailings
Waste rocks

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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http://dx.doi.org/10.1016/j.ijmst.2014.11.003

## 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; $\Delta h$ the hydraulic head difference along the flow direction, m; $\rho_w$ the water density, $kg/m^3$; $g$ the gravity acceleration, $m/s^2$; and $\mu_w$ 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 $\Psi$ (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, $m^3/s$; $\theta_s$ 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 $\alpha_L$ and $\alpha_T$ are the matrix longitudinal and transverse dispersivities, m, respectively; $|q|$ the magnitude of the Darcy flux, m/s; $\tau$ the matrix tortuosity; $D_d$ the free solution diffusion coefficient, $m^2/s$; and $\delta_{ij}$ the Kronecker delta. The effective diffusion coefficient $D_e$ for solutes transport in the matrix is given by free water diffusion coefficient and tortuosity, $\tau D_d$. Typical values for the diffusion coefficient $D_0$, under saturated conditions in soils, range between $1 \times 10^{-9}$ and $2 \times 10^{-9}$ $m^2/s$ [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