Mine Water and the Environment (2005) 24: 172–185 © IMWA Springer-Verlag 2005

Technical Article

Numerical Modelling of Flow and Capillary Barrier Effects in Unsaturated Waste Rock Piles

O. Fala[1], J. Molson[1], M. Aubertin[1*], and B. Bussière[2*]

[1]Dept of Civil, Geological and Mining Eng, École Polytechnique de Montréal, PO Box 6079, Stn Centre-Ville, Montreal, Quebec, H3C 3A7, Canada; [2]Univ du Quebec en Abitibi-Temiscamingue (UQAT), 445 University Blvd, Rouyn-Noranda, QC, J9X 5E4, Canada; [*]NSERC Polytechnique/UQAT Industrial Chair: Env and Mine Waste Mgmt; corresponding author's e-mail: john.molson@polymtl.ca

Abstract. Flow systems in unsaturated waste rock piles were simulated using a two-dimensional numerical model (HYDRUS). The conceptual models are based on homogeneous (unstructured) waste piles, and on structured piles that include either horizontal or inclined fine-grained layers within a coarser host material, forming a capillary barrier system. The approach considers fully transient conditions and uses observed climatic data from a mine site in northern Quebec, Canada. All physical properties of the porous media, including the water retention curves, were obtained from measured data. Different geometric configurations were tested to determine their effect on moisture distribution and water flow, which ultimately control the potential for acid rock drainage (ARD). The simulations begin with a relatively dry initial condition under hydrostatic equilibrium. After an initial transient period, the simulated internal moisture distribution became periodic with a regular pattern of seasonal fluctuations. The simulations suggest that flow can be controlled in such systems using inclined fine-grained layers that retain and divert moisture due to capillary barrier effects. With horizontal layers, the local flow regimes become unstable, causing vertical preferential flow zones to develop below the barriers wherever the local water pressure first exceeds the entry pressure of the underlying coarser material. In this scenario, ARD production can remain high since a large fraction of the internal pile is being flushed. A shallow downward slope in the layers forces drainage toward the outer boundary and maintains lower saturation in the centre of the pile, thus potentially reducing the amount and mobility of ARD.

Key words: acid rock drainage; capillary barriers; numerical modelling; unsaturated flow; waste rock piles

Introduction

Acid rock drainage (ARD) produced by some unsaturated waste rock piles constitutes a large-scale and potentially long-term environmental problem. ARD develops from the oxidation of sulphide minerals such as pyrite and pyrrhotite and is generally characterized by a low pH and high concentrations of dissolved sulphate, iron, and heavy metals (Lefebvre et al. 2001a; Ritchie 1994).

The volume of ARD-generating waste rock makes the environmental impact particularly serious. Some waste rock piles, for example, extend more than 300 m in height and contain more than 500 million m^3 of waste (e.g. McCarter 1990). They are often built over several decades and can be potential sources of ARD for centuries. Variable deposition methods and waste rock properties that change over the lifetime of a rock pile can create an extremely heterogeneous internal structure characterized by wide variations in grain size, density, mineralogy and bedding (Aubertin et al. 2002; Morin et al. 1991).

With surfaces usually exposed to the atmosphere, a waste rock pile can become an acid-generating reactor in which the reaction rate is dependant on the moisture content and supply of oxygen. The process begins with surface recharge, including snow melt, which percolates through a rock pile under generally unsaturated conditions. This process is controlled by gravitational and capillary forces. The flow system may eventually develop preferential flow channels depending on the internal structure and grain size. Thermal gradients that develop from the exothermic sulphide oxidation reactions can add to the complexity by inducing convective flow of gas and water vapour, and can induce local evaporation or condensation (Lefebvre et al. 2001a, b).

Oxidation of the sulphide minerals of the waste rock consumes oxygen, which is replenished through porous layers in the pile by various degrees of diffusion, advection, and thermal convection (Ritchie 2003; Wels et al. 2003). The percolating water, containing sulphide oxidation products, may undergo a series of reactions with the host waste rock, including mineral dissolution, precipitation, metal mobilization and acid buffering. The effluent may eventually seep into the subsurface, or, if the base is relatively impermeable, will discharge out the pile toe, where it can impact surface water. Understanding these complex internal flow systems is critical in order to predict the potential for ARD and to design rock piles that will minimize the environmental impact.

The objective of this paper is to investigate the behaviour of water saturation and water flow in unsaturated waste rock piles, focusing on internal stratification and capillary barrier effects. The flow systems were studied using transient, two-dimensional numerical simulations of both homogeneous and structured (layered) rock piles. Although the systems are conceptual, they are compatible with recent characterization studies of real waste rock piles (Campos et al. 2003; Gamache-Rochette 2003; Martin 2004; Nichol 2002; Wels et al. 2003). All data were obtained from field or laboratory measurements of samples from existing sites. Preferred pile structures are identified and interpreted with respect to their potential effect on water content, flow directions, oxygen diffusion, and the generation of ARD. In a companion paper, Molson et al. (2005) use selected cases of these flow systems as a basis for multi-component reactive transport modeling.

Waste Pile Structure and Characterization

Waste rock piles can be found in many physical and climatic environments, and are deposited at various rates, using a variety of construction methods. Each site is unique in terms of pile structure and internal flow of water. Different methods of rock pile construction and deposition, for example, produce different degrees of compaction and grain size distributions that can have significant effects on the internal distribution and movement of water and gases (Aubertin et al. 2002, 2003; Fala et al. 2003; Morin et al. 1991).

With the commonly used *end-dumping* or *push dumping* construction methods, for example, a layer of finer material is typically found on the surface of the rock pile and a layer of coarser material is found at the base. This layering is particularly noticeable when the grain size distribution is narrowly constrained. As the rock pile grows, the bulk grain size distribution then includes alternating fine and coarse-grained material layers (Fala 2002; Morin et al. 1991). On the other hand, when the grain size distribution is more variable, the vertical pile profile can be irregular and the structure of alternating fine and coarse layers less distinct. Layering inside the pile can be locally enhanced by construction traffic (heavy equipment), which tends to crush and compact the surface material, creating layers that can be up to 1 m thick (Aubertin et al. 2002; Martin 2004) (Figure 1).

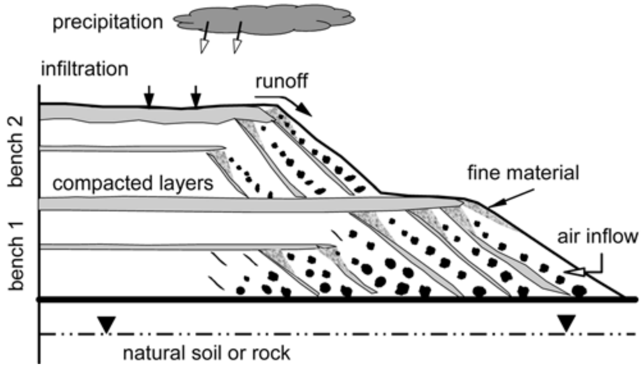

Figure 1. Conceptual cross-section of a waste rock pile showing internal structure and material segregation; waste material becomes coarser toward the base.

The physical hydrogeologic properties of rock piles are critical to understanding and predicting their internal flow systems, yet these properties are often very difficult to determine and interpret (e.g. Noël and Ritchie 1999). A growing effort is therefore being focused on characterizing these systems because the internal flow systems also control the potential for ARD. Some recent characterization work can be found in Barbour and Hendry (2002), Campos et al. (2003), Gamache-Rochette (2003), Nichol (2002), Nichol et al. (2003), Price (2003), Ritchie (1994, 2003), and Smith et al. (1995). Eriksson and Destouni (1997) found that grain diameters can vary by over 6 orders of magnitude (between 1 μm and 1 m), depending on the different processing and depositional methods. Morin et al. (1991) reported that waste rock from hard rock mines typically has a widely distributed grain size curve, with a uniformity coefficient, C_U (D_{60}/D_{10}), of at least 20. At the Laronde waste rock pile in the Abitibi-Témiscamingue region, northern Quebec, Canada, Gamache-Rochette (2003) found C_U values from 250 to 440 for the top-surface material, reflecting the extremely variable grain size. Mineralogy and weathering can also affect grain size distribution.

The grain and pore size distribution within a waste rock pile affects its hydraulic properties, which in turn control internal flow. The relationship between these physical and hydraulic properties is expressed in the hydraulic conductivity and water retention curve (moisture content vs. pressure), which depends on the grain size distribution as well as the density index (or porosity). Water retention generally increases as the particle size and porosity decrease (Aubertin et al. 2003). On the other hand, the saturated hydraulic conductivity (k_s) tends to increase with the average size of the particles (Mbonimpa et al. 2002). However, this trend may be offset by a decrease in porosity, which can occur when the proportion of coarse particles is high enough.

Saturated hydraulic conductivities have been reported to vary from 10^{-2} m/s for waste rock piles composed of volcanic and metamorphic rocks (coarse grained, porosity 35-40%), to 10^{-9} m/s for argillaceous (fine-grained) material (Morin et al. 1991). In lab-scale tests of Laronde Mine waste rock (using sand and silt fractions with grain diameters <5mm), Gamache-Rochette (2003) measured saturated conductivities ranging from 1.9×10^{-7} to 3.7×10^{-5} m/s. At the same site, field infiltration tests at various scales gave values ranging from 10^{-5} to 0.015 m/s. Differences were attributed to scale effects and different grain size distributions in the lab and field samples.

Most waste rock piles also have spatially variable hydraulic properties due to variations in moisture content, mineralogy, and/or grain size distribution (e.g. Smith and Beckie 2003). Stratification within the pile, for example, may lead to higher moisture contents within the less permeable layers of denser or finer material. As stated above, local-scale stratification is often associated with mine machinery operations whereas larger-scale material segregation and layering occurs during waste deposition along the external slopes. The stratigraphy can also be enhanced by material degradation when relatively coarse particles are broken down mechanically or by atmospheric weathering. The texture of these layers tends to enhance water retention relative to the unaltered waste rock, which will influence the degree of saturation and flow of water within the pile. This has been observed, for example, at the Laronde Mine, Quebec (Gamache-Rochette 2003), and at the Goldstrike Mine, Nevada (Martin 2004).

Flow Systems within Waste Rock Piles

The internal moisture distribution and flow systems in heterogeneous waste rock piles are difficult to measure, interpret, and predict. Extreme variations of grain size, porosity, and water saturation in space and time further complicate the effort. Nevertheless, recent investigations (outlined below) have begun to provide insight into these systems, including effects of preferential flow and capillary barriers.

Preferential flow can be caused by continuous macropores or by vertical, horizontal, or inclined layers of relatively high hydraulic conductivity that often control the movement of water within a pile. This has been observed in laboratory (waste rock models) and field scale (waste pile) systems by, among others, Gamache-Rochette (2003), Li (2000), Morin and Hutt (1994), Smith et al. (1995), and Zhan (2000). When the layering occurs as a fine-grained unit above a coarse-grained zone, a capillary barrier is formed in which water is preferentially retained in the fine grained material due to capillary forces (Bussière et al. 2003b; Nicholson et al. 1989). Capillary barriers have been proposed for use in waste rock piles to control air and water flow (Lefebvre et al. 2001b; Poulin et al. 1996) and field installations and performance of capillary barriers have been described by Dagenais et al. (2002), Ricard et al. (1997), Wilson (2003), Woyshner and Yanful (1995) and Zhan et al. (2001).

These complex flow systems must be well understood to predict oxygen diffusion and advection in waste rock piles since the diffusion rates are highly saturation-dependent. Aachib et al. (2002, 2004) and Mbonimpa et al. (2003) developed conceptual models for predicting oxygen diffusion rates through partially-saturated porous material. Ritchie (2003) reviews some of the important processes and physical properties affecting gas transport through sulphidic material.

The flow of water, transport of aqueous components, and dissolution/precipitation of solid minerals are closely coupled processes in mine tailings and rock piles, and they interact in complex ways to generate ARD. Numerical models are often the best way to study these interactions, to evaluate parameter sensitivity, and to compare closure or remediation scenarios. Eriksson and Destouni (1997), for example, applied a probabilistic Lagrangian transport model to simulate preferential flow and copper leaching from waste rock piles. They showed that flow channelling was a probable explanation for discrepancies between observed and simulated effluent concentrations. Their simulations suggested that peak ARD loads may be reduced and dispersed over longer time scales in preferential flow systems. Oldenburg and Pruess (1993) completed a detailed modeling study that showed complex flow behaviour within capillary barriers, including flow exclusion and leakage. They also demonstrated the sensitivity of flow instabilities to various numerical discretization schemes. The influence of length and inclination on capillary barrier response was simulated by Bussière et al. (2002, 2003a, b).

Several modelling approaches have been developed to simulate the interaction between flow and transport through sulphide-bearing mine waste materials. Gerke et al. (1998), for example, coupled the SWMS_2D flow model (Simunek et al. 1994) to a finite element reactive transport model to simulate ARD from unsaturated sulphide-bearing overburden waste from lignite mining. They incorporated heterogeneous physical and chemical waste properties, including spatially variable random fields of grain radius and hydraulic conductivity. A more advanced finite volume model (MIN3P) was applied by Bain et al.

(2001) and Mayer et al. (2002) for ARD prediction, and Lefebvre et al. (2001b) applied an integrated finite difference model (TOUGH-AMD) to simulate ARD from a waste rock pile. In all cases, the flow system played a critical role in the generation and transport of ARD. Hence, further work was deemed necessary to better understand flow conditions in representative waste rock piles.

Simulation Approach

The flow systems presented here were generated using the well-known HYDRUS 2D model (Simunek et al. 1999) for transient, unsaturated flow. Assuming an incompressible porous medium, and an isothermal, dilute fluid, the governing flow equation can be expressed in Cartesian (x,z) coordinates as the mixed form of the Richards (1931) equation:

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

where ψ is the suction pressure head (L), θ is the volumetric water content, t is time (T), k_x and k_z (L/T) are the horizontal and vertical components of the pressure-dependent hydraulic conductivities, and x,z (L) are the horizontal and vertical coordinate directions, respectively. HYDRUS uses the finite element method and was applied here using triangular element grids.

Due to the highly nonlinear behaviour of the hydraulic conductivity and water content terms in equation (1), a stable and mass-conservative solution can be difficult to obtain. The problems are compounded at large scales, which may require very fine grids and large computational resources. Numerical instability and oscillations have been observed in waste rock pile simulations, for example, by Fala (2002), Martin (2004) and Wilson et al. (2000). Several numerical methods have been proposed to help improve mass balance, including the robust temporal weighting scheme of Celia et al. (1990). Although the HYDRUS model uses the Celia scheme, some preliminary simulations of the waste rock piles considered here showed early signs of oscillatory behaviour in the water content solution, indicative of convergence problems (Fala 2002).

In order to improve convergence and mass balance for the simulations here, the systems were scaled using the principle of similitude. Normally applied to lab-scale experiments in order to ensure physical realism and equivalency at larger scales (Kline 1965; Munson et al. 1994), similitude can also be used when applying numerical models to difficult problems. In the present study, the approach involved a simple scaling (by a factor of 10^3) of the boundary recharge, evapotranspiration, moisture content, and hydraulic conductivity (see details in Fala et al. 2001). Following the solution, the system was back-scaled to return to the original conditions.

Convergence and mass balance were verified for each simulation and the model-calculated hydraulic conductivities (based on the simulated pressures) were verified to be consistent with those entered into the model (following the approach of Chapuis et al. 2001). The numerical approach assumes isothermal conditions and does not account for vapour flow, pile consolidation, or changes in pore volume due to mineral precipitation and dissolution.

Boundary Conditions and Grid

The numerical simulations are based on axisymmetric and 2D Cartesian models of unsaturated waste rock piles constructed over a relatively flat surface, with possible internal bedding and stratigraphy (Figure 2). In the axisymmetric systems, the waste rock pile was assumed to be radially symmetric about the vertical centerline (which becomes the left boundary of the model), while the 2D Cartesian system assumes mirror symmetry about the centerline, hence implying a transverse dimension much greater than the simulated section length. The simulations were completed on triangular element grids with element dimensions ranging from 5 cm in the fine-grained layers (where present) to 20 cm near the base of the pile. The grids typically contain on the order of 18,000 nodes and 35,000 elements (Figure 2).

Across the upper boundary and end-slope, a seasonally-varying recharge was assigned, while the left symmetry boundary was assumed to be no-flow. The surface recharge boundary conditions were based on observed average daily precipitation and evapotranspiration from the Latulipe mine site in northwest Quebec for a 20-year period between 1981 and 2001 (Table 1, Figure 3). The water table was assumed to lie below the base of the pile (base elevation = 0 m) where a free drainage condition was applied with a pressure head of -5 m (50 kPa suction), which is sufficiently low to attain residual saturation. This condition reproduces the effect of a coarse, well-drained layer that is often found at the base of a waste rock pile. For the initial condition, a hydrostatic pore pressure distribution was assumed from the base to the top of the pile.

Material Properties

The numerical simulations are based on waste rock piles constructed with either a homogeneous sand

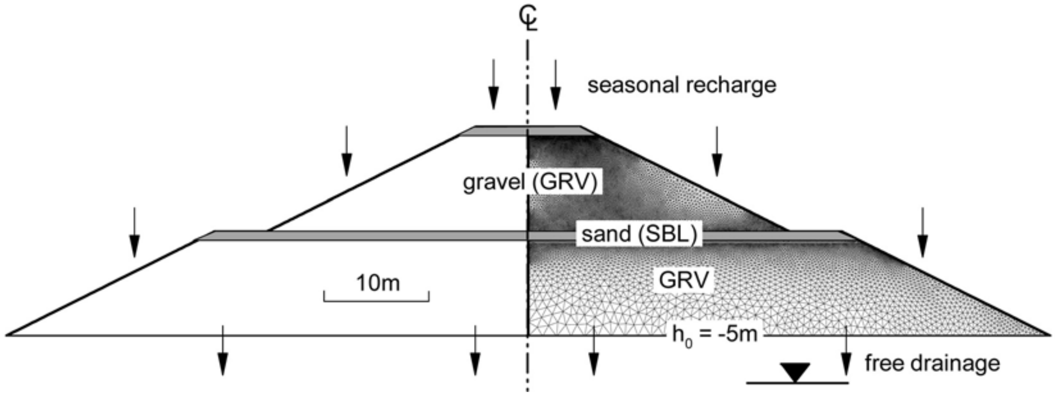

Figure 2. Idealized model geometry, boundary conditions and finite element grid; the numerical simulations consider only the right (2D Cartesian or axisymmetric) section

Table 1. Observed climatic conditions (precipitation and evapotranspiration, in cm/d) used in the numerical model (see Figure 3)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Precip.	0.182	0.15	0.191	0.22	0.258	0.307	0.302	0.314	0.324	0.293	0.231	0.230
Evap.-Tr.	0	0	0	0.046	0.237	0.339	0.407	0.345	0.21	0.089	0	0

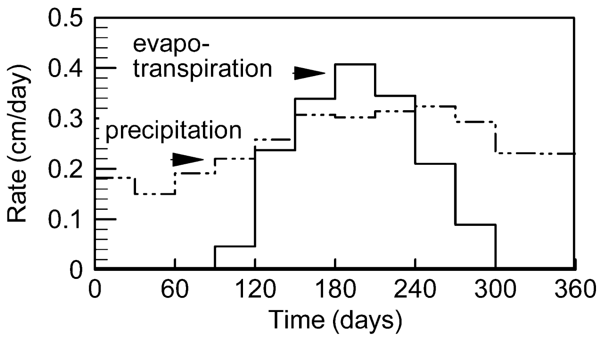

Figure 3. Observed precipitation and evapotranspiration from Latulipe, Quebec, as used in the numerical model (data provided in Table 1)

(SBL) or gravel (GRV) material, or layers of SBL within a host GRV. These materials were used by Bussière et al. (2002, 2003a) in physical experiments using an instrumented infiltration box, and in numerical simulations of capillary barrier effects with inclined systems. The granulometric curves are shown in Figure 4. Bussière (1999) studied the hydraulic properties of these materials and determined the parameters for the van Genuchten (1980) model given by:

$$\theta_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha_v \psi)^{n_v}} \right]^{m_v} \qquad (2)$$

$$k(\theta_e) = k_s \theta_e^{\ell} \left[1 - \left(1 - \theta_e^{1/m_v} \right)^{m_v} \right]^2 \qquad (3)$$

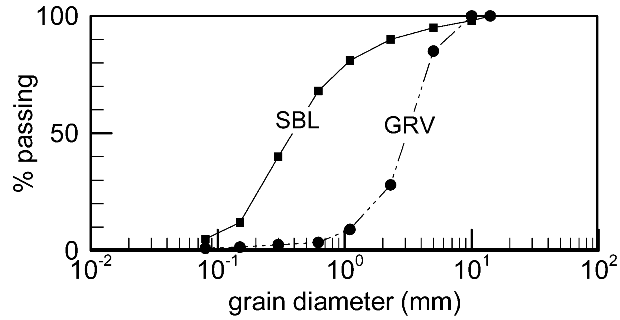

Figure 4. Grain size distribution curves for the sand (SBL) and gravel (GRV) materials as used in the numerical model (after Bussière et al. 2003b)

where θ_e is the effective water saturation, θ is the (volumetric) water content, θ_s is the saturated water content, θ_r the residual water content, ψ is the suction pressure, α_v, m_v, n_v are the van Genuchten (1980) parameters, $k(\theta_e)$ is the saturation-dependent hydraulic conductivity, k_s is the saturated hydraulic conductivity and ℓ is a parameter representing the degree of pore connection ($\ell = 0.5$).

The van Genuchten parameters used for the current simulations are presented in Table 2 and the corresponding curves are shown in Figure 5. The SBL and GRV materials have a rather low water retention capacity since they correspond to coarse grained materials with a relatively uniform grain size distribution. The residual moisture contents for the SBL and GRV are 0.01 and 0.00, respectively, and the respective air entry values (ψ_a) are 3.5 and 0.20 kPa. The hydraulic functions reflect the assumption that as the water content approaches the residual water

Table 2. Values of the van Genuchten (1980) parameters used in this study (see Figure 5) (after Bussière 1999)

	θ_r	θ_s	α_v(m^{-1})	l	n_v	k_s *(m/s)*
Gravel	0.00	0.39	14960	0.5	1.45	4.7×10^{-3}
Sand	0.01	0.29	3	0.5	3.72	5.1×10^{-5}

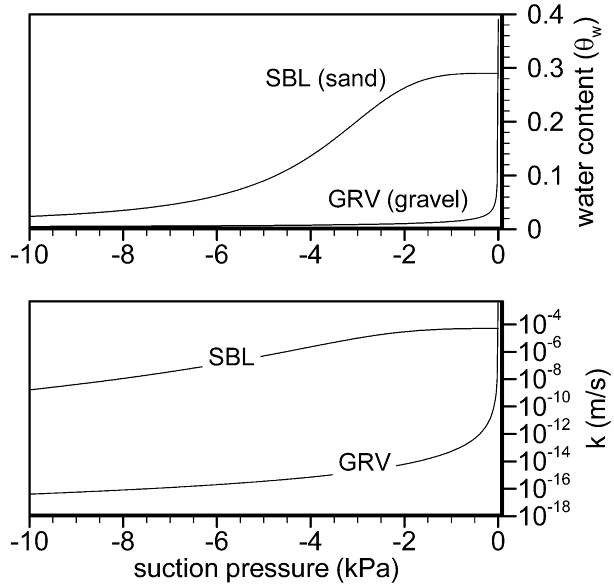

Figure 5. Water content and hydraulic conductivity curves used in the model for the sand (SBL) and gravel (GRV) materials (see Table 2 for the corresponding van Genuchten parameters)

content for each material, the effective hydraulic conductivity approaches zero.

Numerical Simulation Results

In this section, six flow simulation scenarios (S1 to S6) were chosen to illustrate the behaviour of water in unsaturated waste rock piles (Table 3). The effects of system geometry, material properties and angle of the capillary barriers were of particular interest.

The first four scenarios assume an axisymmetric geometry. Scenarios S1 and S2 are homogeneous piles composed of gravel (GRV) and sandy (SBL) materials, respectively. Scenario S3 includes a horizontal sand layer within the host gravel while in scenario S4, the sand layer is inclined by 3.4° toward the pile slope. The 3.4° inclination was the minimum angle for which flow was retained completely within the capillary barrier. Other angles were studied by Fala (2002) but are not shown here. Scenario S5 is identical to S4 but assumes a 2D Cartesian geometry with the sand layers inclined by 8° (which was the critical angle for the Cartesian case). Scenario S6 is also a 2D Cartesian system, and includes a heterogeneous distribution of sand layers.

Simulation S1 (Figure 6) shows that in a homogeneous pile made of a coarse (gravel) material (initially dry under hydrostatic conditions), water infiltrates the pile at a uniform rate and forms a partially saturated wetting front with a relatively low moisture content (θ=0.1, porosity n = 0.39, water saturation S_w (V_w/V_v) ≈25%). After one year, the wetting front reaches a depth of about 5m; it reaches a quasi steady-state condition after 5 years. Fala (2002) shows additional simulations that require on the order of 10 years to reach steady state conditions.

The rate of advancement of the front is a function of the precipitation and evapotranspiration rate, and of the moisture content of the material near the surface of the pile. In this case, the imposed rate of evapotranspiration is greater than the precipitation rate for the three warmest months of the year: June, July, and August. The high evapotranspiration increases the water suction and decreases the residual water content to zero near the surface, which induces upwards water displacement. The precipitation rate is higher than the evapotranspiration rate for the remainder of the year.

The changes in saturation with time for simulation S1, at various locations throughout the pile, are provided in Figure 7. The wetting front arrival times can be clearly seen; for example, at point 5 near the left boundary, the front arrives at about 1.6 years. For most locations, the initial transient period lasts approximately 2-3 years, after which the water content

Table 3. Characteristics of simulations S1 to S6

Case	Thickness[1]	Angle of capillary barriers[2]	Geometric Configuration	Materials[3]
S1	-	-	Axisymmetric, homogeneous	GRV
S2	-	-	Axisymmetric, homogeneous	SBL
S3	0.5	0	Axisymmetric, horizontal layers	GRV \ SBL
S4	0.5	3.4	Axisymmetric, inclined layers	GRV \ SBL
S5	0.5	8	2D, inclined layers	GRV \ SBL
S6	-	0	2D, heterogeneous	GRV \ SBL

[1]Thickness of the fine-grained layers, m; [2]inclination, in degrees; [3]material identification: host\layers (see Table 2)

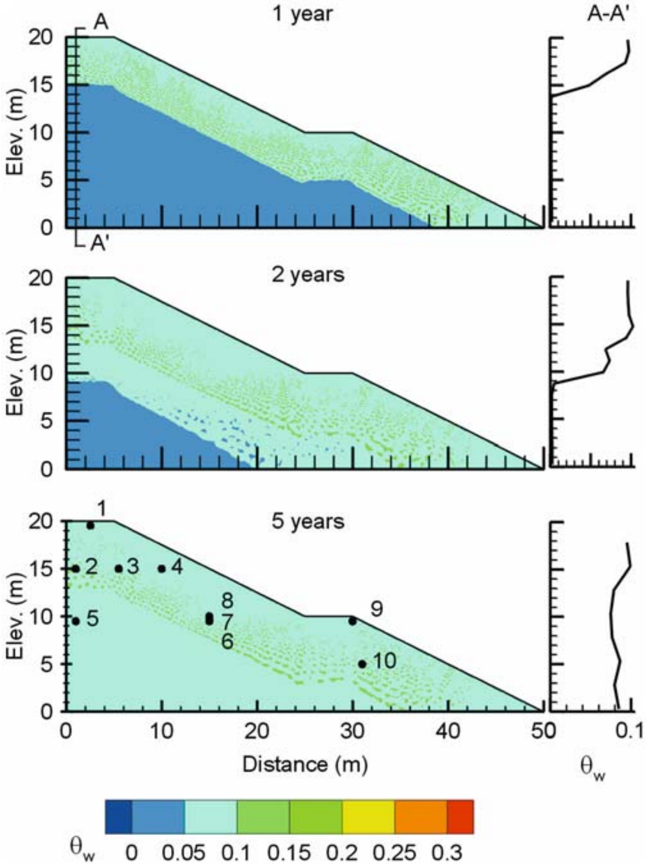

Figure 6. Simulation S1, axisymmetric system, homogeneous gravel; water content after 1, 2, and 5 years in space and along vertical profiles A-A' (columns at right); numeric labels refer to locations of monitor points for arrival curves in Figure 7

changes in a regular annual cycle, influenced only by the seasonal recharge.

In simulation S2 (Figure 8), in which the gravel is replaced by a sandy material, the depth of the wetting front after 1 year increases to about 16.5 m. However, the maximum water content is significantly lower than within the GRV, on the order of 0.03 at the front ($n = 0.29$, $S_w \sim 10$ %). Relative to the GRV, the wetting front is displaced more rapidly but there is less local water accumulation. This behaviour is consistent with the relatively higher residual moisture content of the sand compared with the gravel. At high suction (low saturation), the relative permeability of the sand is higher than that of the gravel; therefore, the wetting front advances further, leaving a lower water saturation behind. The transient behaviour of water saturation at points within the pile was similar to that observed in the homogeneous GRV pile (Figure 7), but with lower maximum saturations of about 0.04 (not shown). With the higher relative permeability of the SBL, the wetting front arrival times were also somewhat earlier; for example, at point 5, the front

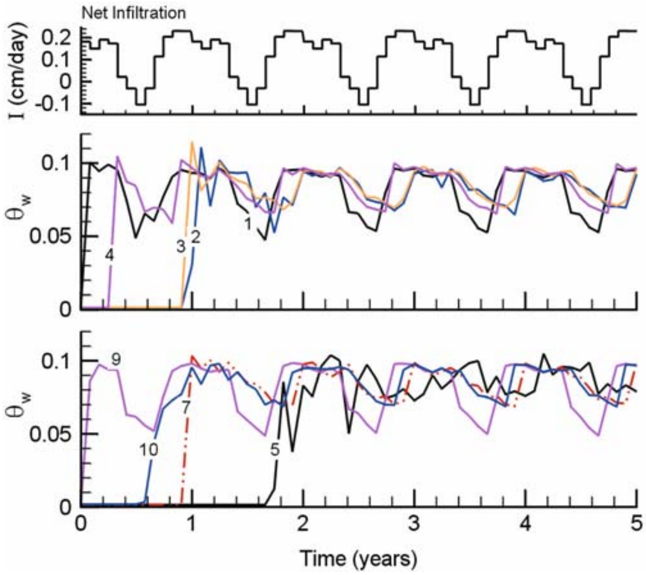

Figure 7. Saturation vs. time at various points within the waste pile: simulation S1, homogeneous gravel (net infiltration is shown at top for comparison); locations of monitoring points are shown in Figure 6

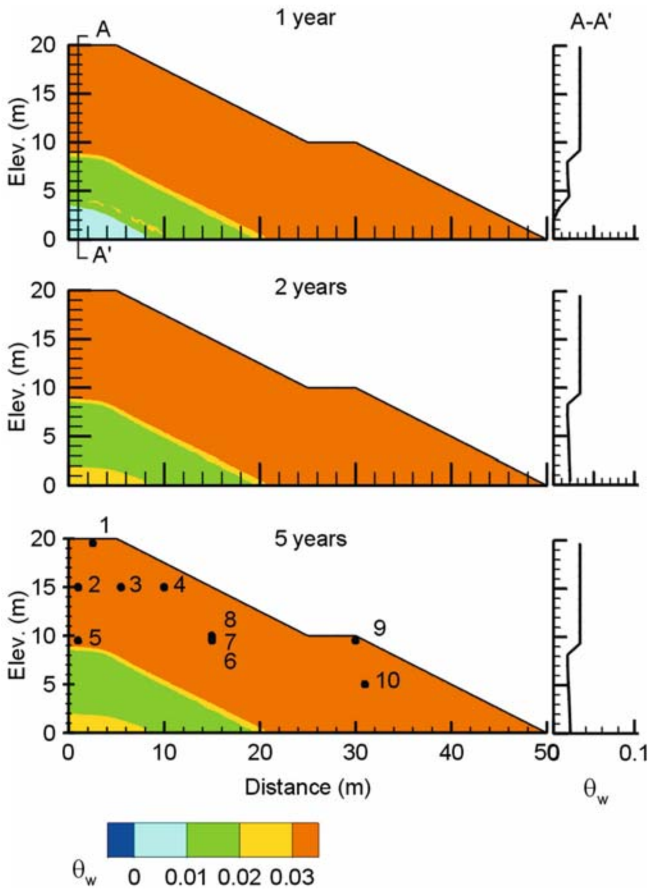

Figure 8. Simulation S2, axisymmetric system, homogeneous sand; water content after 1, 2, and 5 years; vertical profiles at x=1m (A-A') are shown to the right (note the lower water content scale relative to the other simulations)

arrives after only 0.4 years, compared to 1.6 years in the homogeneous GRV.

The simulations therefore show that the water content and depth of the wetting front depend significantly on the material characteristics, and also on the initial and boundary conditions. They depend much less on the geometric configuration when considering a single homogeneous material (for examples with different geometry, see Fala 2002).

Simulation S3 represents the case in which two horizontal layers of SBL material (each 0.5 m thick) are placed within the bulk GRV host material (Figure 9). In this case, the GRV material near the boundary slope essentially behaves as if the SBL layers did not exist. The wetting front penetration depth and the maximum water saturation after 1 year, for example, are the same as in simulation S1. At the same time, more water tends to accumulate and flow within the SBL layers than in the surrounding GRV. The SBL layers are functioning as capillary barriers, attracting water and inhibiting it from entering the coarser underlying material. Towards the bottom of each SBL layer, at the interface with the GRV, the water content reaches a maximum of about 0.27 ($S_w \approx 97$ %). After a few years, the quasi-saturated section within the SBL layer attains a maximum thickness of 8-10 cm.

As water accumulates in the SBL and the pressure reaches the water entry pressure of the underlying GRV, water begins to infiltrate the coarser material (Figures 9, 10). This infiltration, or leakage, occurs along pseudo-random preferential flow paths located, in this case, approximately every 2 to 5 m along the SBL layer. The infiltration first occurs due to small, often imperceptible geometric irregularities in the grid at or immediately below the SBL/GRV interface, and due to differences in the hydraulic characteristics of the two materials (Fala 2002). In a real waste rock pile with similar layering, these flow channels could occur naturally due to intrinsic heterogeneities and pore-scale variations in the moisture content.

The SBL material in scenario S3 begins transporting water to the underlying GRV by the second month, and the vertical flow channels are almost completely developed within three years from the beginning of the simulation. The saturation within each channel reaches a maximum of about 20%, while the host GRV between the channels remains relatively dry. However, most of the waste rock pile in this scenario is still being flushed.

Changes in moisture content over time for simulation S3 are shown in Figure 11. Similar to the homogeneous cases, the initial transient period lasts 2 to 3 years,

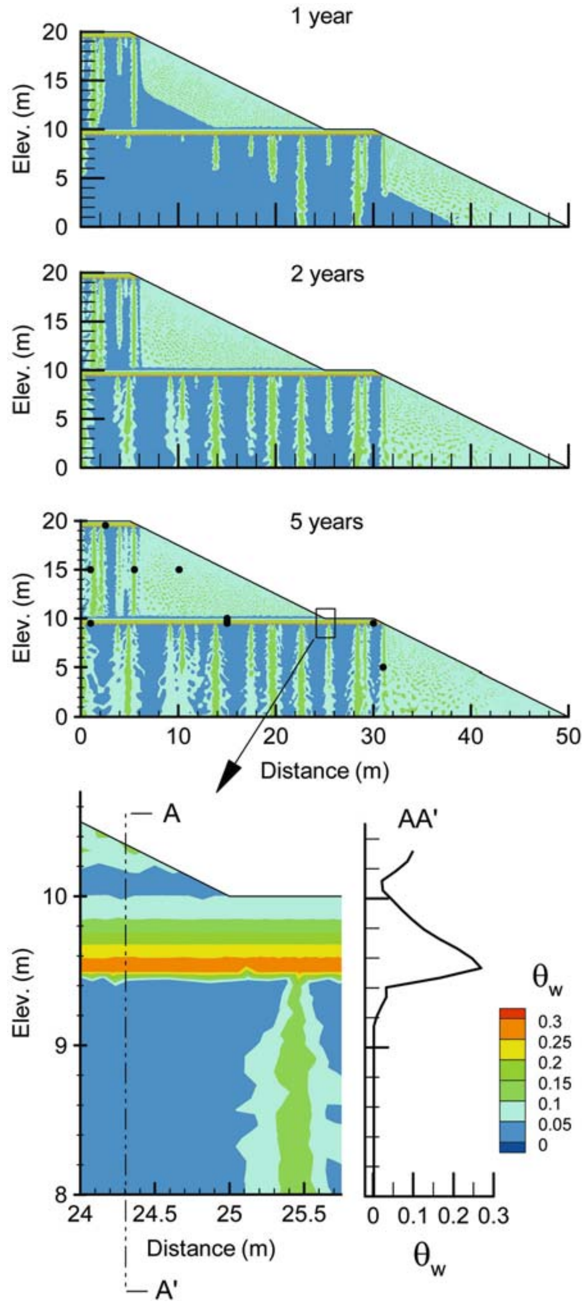

Figure 9. Simulation S3, axisymmetric system, horizontal layers, water content after 1, 2, and 5 years; circles refer to location of monitoring points for arrival curves in Figure 11.

after which the water content follows an annual cycle. Saturation is highest at the bottom of the two sand layers (points 1, 5, 6, and 9), and seasonal fluctuations are more attenuated within the deeper sand unit. Between the middle of the lower sand layer (point 7) and the top (point 8), the saturation decreases from about 0.15 to 0.05 and the seasonal variation becomes more attenuated. Above the lower sand layer (points 2, 3, and 4) and below it (point 10), the saturation within the gravel follows a similar cyclical trend, with values ranging from 0.06 to 0.12.

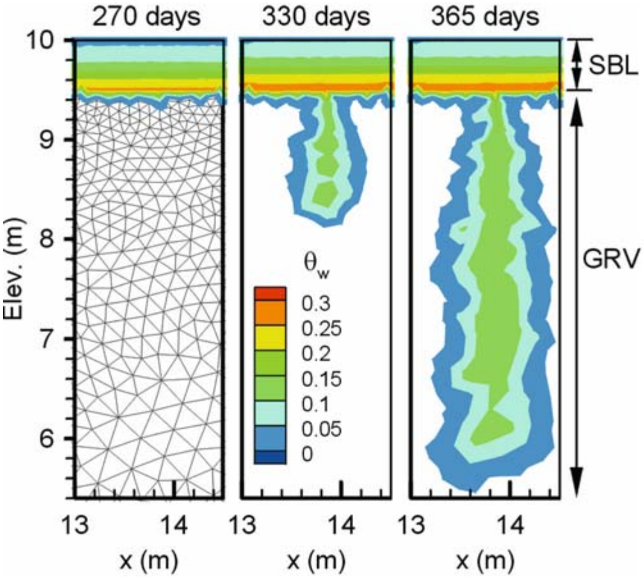

Figure 10. Detail of simulation S3 showing finite element grid and development of a preferential flow zone from the lower horizontal sand layer into the underlying gravel; contour flood cutoff is $\theta_w = 0.01$

In Scenarios S1 to S3, water is flushed through most of the waste rock pile, either uniformly (S1, S2) or within preferential flow zones (S3). Scenario 4 (S4) was designed to reduce this flushing by using SBL layers sloping downwards toward the outside of the dump at an angle of 3.4° (Figure 12). As in Scenarios S1 to S3, scenario S4 also assumes an axisymmetric geometry.

The flow simulation for scenario S4 shows that the percolation points at the SBL-GRV interface have now disappeared and the water that accumulates in each of the SBL layers is diverted towards the outside of the dump. The inclined layers have therefore prevented deep infiltration, leaving the core relatively dry. Only a single vertical flow channel appears near the intersection of the SBL and the pile surface (at the DDL, or down-dip limit) (Bussière et al. 2003a; Ross 1990). Consequently, during the entire simulation period, the water content in the center of the rock pile remains low while the water content increases towards the outside of the rock pile. Conceptually, the inclined sand layers are functioning as lateral 2D capillary barriers which channel flow and divert water towards the outside of the dump. The implications for ARD are presented in the next section.

Scenarios S1-S4 assumed a circular, axisymmetric waste rock pile. To evaluate the effect of pile geometry, these scenarios were re-run assuming a linear 2D Cartesian geometry, using an identical grid and the same boundary and initial conditions. These new results (not shown) produced essentially the same behaviour as their equivalent axisymmetric cases. In case S3, some minor differences were observed

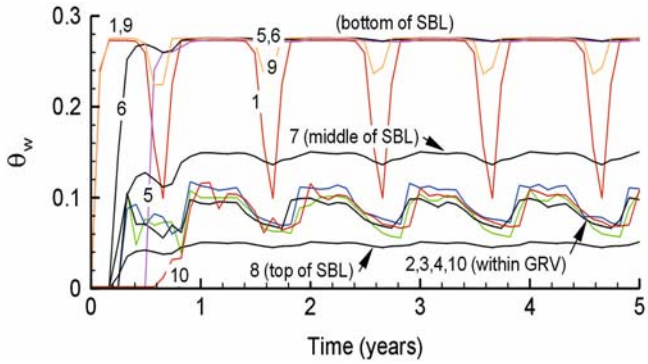

Figure 11. Water content vs. time for simulation S3 at selected points in the pile; monitoring point locations are shown in Figure 9

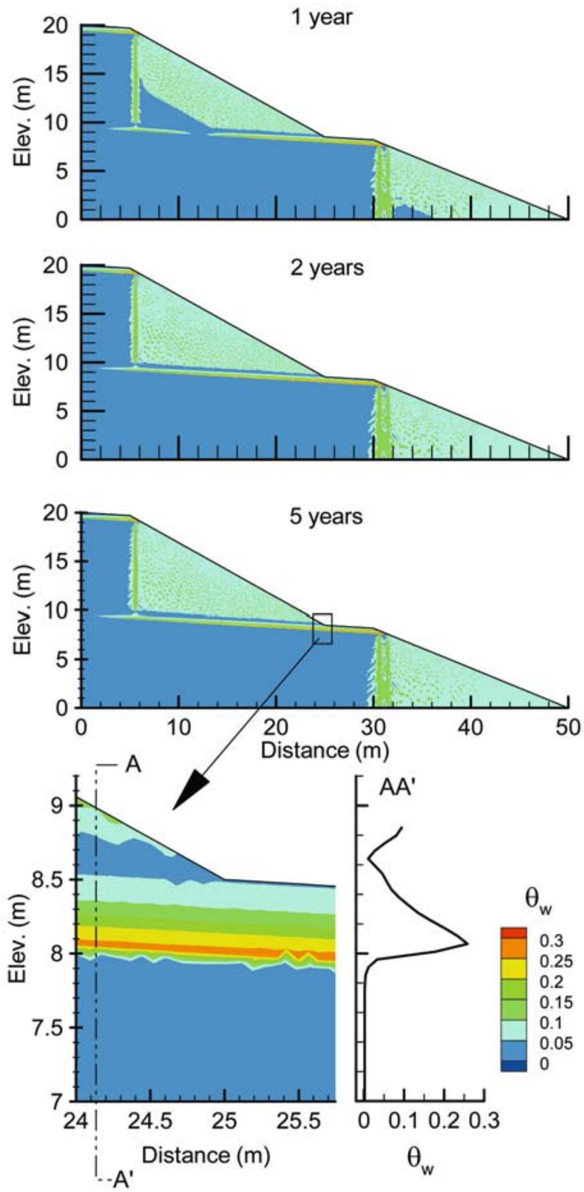

Figure 12. Simulation S4, axisymmetric system, inclined SBL layers (3.4°); water content after 1, 2, and 5 years; exploded view and vertical profile are also provided

in the location of the vertical preferential flow channels, with the axisymmetric case producing a slightly greater degree of preferential flow or leakage. However, when case S4 (with layers inclined 3.4°) was repeated assuming a Cartesian geometry, the local flow system within the SBL sand layers remained unstable and produced almost as much leakage as in the horizontal case of S3. This difference in behaviour is attributed to the influence of pile geometry (i.e. circular vs. elongated) on internal flow and lateral discharge.

In the 2D Cartesian equivalent of case S4, leakage through the vertical flow channels gradually disappeared as the slope of the SBL layers was increased. At an inclination of about 8° (case S5, not shown), all discharge was again retained within the SBL layers and the down-dip limit reformed at the end of each layer near their intersection with the pile surface (about 6 m and 32 m from the left boundary, for the upper and lower SBL layers, respectively). The results suggest that the efficiency of the SBL capillary barriers in diverting flow from the pile interior improves as the barrier slope, and hence flow rate, increases. This is in agreement with the diversion capacity of inclined capillary barriers (e.g. Bussière et al. 2003a). For a given barrier inclination and recharge rate, axisymmetric waste piles also appear more effective at diverting water and reducing the degree of leakage.

Simulation S6 (Figure 13) shows the case of unsaturated flow within a strongly heterogeneous (but still idealized) system. This 2D Cartesian system was conceived to represent a pile where the waste rock was assumed to have been push-dumped over the edge of an existing slope (Fala 2002). Again in this case, water flow depends on the distribution of fine material layers within the pile. Compared to a homogeneous pile or a pile with horizontal layers, water infiltrates more quickly and deeply within the heterogeneous pile, following the fine material zones (assuming identical boundary and initial conditions).

Hence, from these results, it can be said that heterogeneous and/or stratified conditions seem to favour the development of non-homogeneous flow. In some cases, these conditions may have a more detrimental effect on the environment, as discussed below.

In addition to those simulations presented here, several other cases were also run, but these showed generally similar behaviour (and therefore are not shown). Increasing the thickness of the SBL layers (horizontal or inclined) from 0.5 to 1.0 m, for example, produced only minor differences. Since

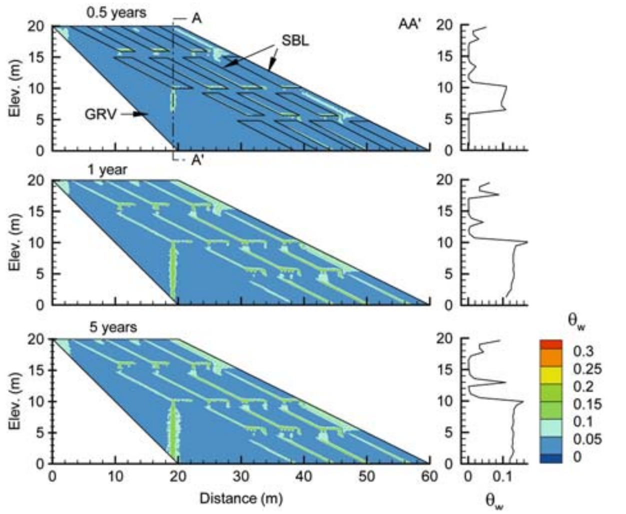

Figure 13. Simulation S6, 2D Cartesian heterogeneous system; water content after 0.5, 1, and 5 years; locations of SBL zones are superimposed on top figure

only the lowermost 8-10 cm of each layer approached saturation in these scenarios, an increase in layer thickness would not be expected to play a major role. Further scenarios are presented in Fala (2002).

Implications for Water Quality

The waste rock flow systems predicted in this study have important implications with respect to the water quality in the pile. In the case of ARD-producing wastes, the simulations provide valuable information on the moisture distribution (i.e. spatial and temporal changes in saturation), as well as flow rates and flow directions, all of which affect the generation and mobility of sulphide oxidation by-products. While the impact on ARD depends on many additional factors, including residence times and geochemical reactions, a number of observations can nevertheless be made.

Scenarios S1 and S2 represent possible worst-case scenarios with respect to ARD since the complete pile is being flushed and local water contents remain well below saturation, allowing relatively unimpeded inflow of oxygen. Although the maximum degree of saturation in S2 (homogeneous SBL) is almost an order of magnitude less than that for the homogeneous GRV case (0.03 vs. 0.3), this difference may not significantly affect the bulk oxygen diffusion rate, since in both cases the rate will be near the maximum possible under dry conditions. Results from Aachib et al. (2004) and Mbonimpa et al. (2003) show, for example, that the effective diffusion rate for oxygen changes very little within this range (Figure 14). The low degree of saturation also favours the movement of air by advection and convection in the pile (e.g. Lefebvre et al. 2001b). Oxygen can therefore easily advance throughout the pile and oxidation by-products can be rapidly discharged with the water. The smaller grain size of the SBL material may also increase the rate of sulphide mineral oxidation since the reactive surface area will be higher (Molson et al. 2005).

Surface recharge is identical for scenarios S1 and S2 (and for all other cases shown here); therefore, the total volumetric discharge (m^3/s) of acidic effluent from the base will also be identical. In the SBL waste pile (S2), this discharge will, however, be at a higher flow rate v (m/s).

In scenario S3 with horizontal SBL layers, discharge is more focused through preferential flow channels. However, as most of the waste rock pile is still being flushed, ARD production would likely remain high. This behaviour is confirmed numerically in the ARD transport simulations of Molson et al. (2005).

The relatively high saturations within the sandy layers may have a secondary effect on ARD by reducing the rate of oxygen advection and diffusion, which are the driving forces for sulphide oxidation. Within the bottom of each sand layer, for example, where saturations are over 95%, the local effective oxygen diffusion rate will be reduced by up to 4 orders of magnitude relative to a state of residual saturation (Figure 14 and Aachib et al. 2002, 2004). Within the vertical preferential flow zones, however, the maximum degree of saturation is only 20%; therefore, oxygen diffusion from the outer boundary can continue relatively unimpeded and ARD will not be significantly reduced.

Scenario S4 with inclined SBL layers shows much greater potential for limiting or controlling ARD by controlling water movement. First, the preferential flow zones predicted from the horizontal SBL layer case (scenario S3) are now completely eliminated. Most of the underlying core of the pile therefore remains relatively dry, and any oxidation products there would remain immobile. Flow, and any acidic discharge, remains channelled in the inclined SBL layers as far as their down-dip limit, which in this case is close to the intersection with the pile surface. The discharge zone is therefore reduced to a peripheral ring near the pile toe. For a given pile height, the radius of this ring will decrease as the pile slope is increased. Long-term control of ARD could be achieved if the SBL layers and outer GRV zone are constructed using low or non-reactive waste rock material. The higher moisture content towards the outer pile surface may also tend to reduce oxygen diffusion and advection into the dump compared to the case with horizontal SBL layers.

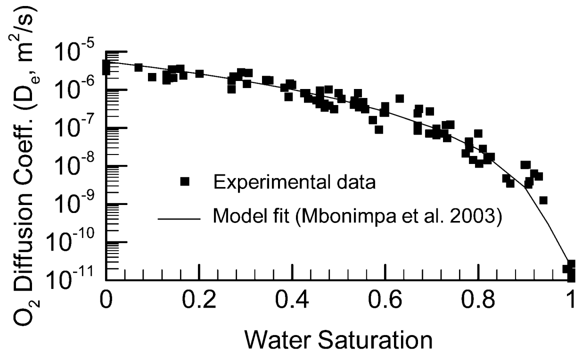

Figure 14. Effect of degree of saturation on the effective diffusion coefficient for oxygen (after Mbonimpa et al. 2003)

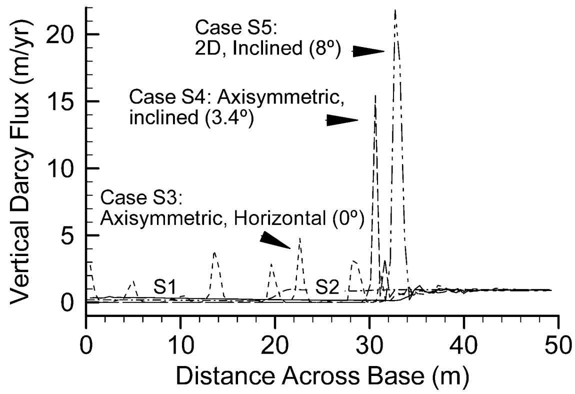

Figure 15. Comparison of Darcy flux profiles across the pile base, after 5 years, scenarios S1-S5

One means of quantifying the effectiveness of the preceding waste rock pile models in controlling ARD is by comparing the fluid discharge across the pile base (Figure 15). In scenarios 1 and 2, the water discharge (Darcy flux) is relatively uniform and remains below 1.0 m/yr across the entire base. In scenario 3 (with horizontal layers), the effect of the preferential flow zones is evident as a series of discharge peaks reaching up to 5 m/yr. Between these zones, the discharge is less than 0.1 m/yr. In the axisymmetric case with inclined layers (S4), there is only a single major discharge zone, at about 30 m, where the discharge reaches 15 m/yr. Similarly, in the 2D Cartesian case (S5), but with layers inclined 8°, the peak discharge increases to about 22 m/yr.

Although the peak discharge in the two inclined cases is significantly higher than in the homogeneous or horizontal layer cases, the discharge is localized and hence may be easier to collect and treat. Also, in some cases, it could be possible to place non acid-generating materials in the discharge areas, to limit ARD production. Such alternative disposal scenarios are being investigated as a means to alleviate generation of contaminated leachate from waste rock piles.

Conclusions

The simulations presented in this study provide insight into the behaviour of unsaturated flow systems in waste rock piles. Homogeneous piles showed a more uniform wetting front and moisture distribution, which may promote contaminant mobility. The maximum moisture content in the homogeneous sand piles was generally about one tenth that of the gravel. Structured piles with horizontal fine-grained layers led to vertical preferential flow paths in most of the pile, potentially augmenting contaminant transport. Structured, heterogeneous piles produced numerous flow channels, which may also tend to increase the rate of ARD. The simulations suggest that it takes 2-3 years for water saturation to pseudo-equilibrate from the relatively dry initial conditions assumed here. Thereafter, saturation in the pile followed an annual cycle dependent on the seasonal recharge.

The simulations also suggest that water flow in a waste rock pile can be controlled using fine-grained layers inclined downwards towards the outer pile boundary. These layers form a capillary barrier, preventing the percolation of water towards the center of the pile and diverting water toward the exterior. Under these conditions, a large proportion of the rock pile remains dry, which can help reduce ARD. For homogeneous and horizontally-stratified piles, 2D axisymmetric and Cartesian geometries produced essentially the same water saturation distributions and flow behaviour. With inclined sand layers, however, the axisymmetric case showed a somewhat more favourable behaviour, with complete flow diversion attained at a lower slope angle (3.4° (6%) slope, case S4 vs. 8° slope, case S5).

The question then becomes: How can a waste rock pile be constructed economically with this type of stratification? Material segregation, which naturally occurs from some types of construction methods (e.g. end-dumping), could be a possible solution. However, several practical problems remain, including how to control granular segregation and layering to the standards required. Additional numerical and field tests are being initiated in order to resolve these questions.

Although the simulations suggest that inclined capillary barriers would be advantageous for controlling ARD, the increased water content and pore pressures near the face could also increase the risk of erosion and slope instability. Incorporation of additional design measures such as drainage systems may be required to reduce this risk.

The implications for ARD generation and control are here based on the flow system alone. A more complete analysis requires accounting for reactive transport of the oxidation by-products, including pH-buffering, mineral dissolution, and precipitation reactions. These issues are being explored in more advanced simulations, including those presented by Molson et al. (2005).

Acknowledgements

This research was financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the partners of the NSERC-Polytechnique-UQAT Industrial Chair in Environment and Mine Waste Management (www.polymtl.ca/enviro-geremi).

References

Aachib M, Aubertin M, Mbonimpa M (2002) Laboratory measurements and predictive equations for gas diffusion coefficients of unsaturated soils. Proc, 55th Canadian Geotechnical Conf, Canad Geotech Soc, Niagara Falls, Ontario, p 163-172

Aachib M, Mbonimpa M, Aubertin M (2004) Measurement and Prediction of the Oxygen Diffusion Coefficient in Unsaturated Media, with Applications to Soil Covers. Water, Air Soil Poll 156: 163-193

Aubertin M, Bussière B, Bernier LR (2002) Environnement et gestion des rejets miniers. Presses Internationales de Polytechnique, Ecole Polytechnique, Montreal, Canada, on CD-ROM

Aubertin M, Mbonimpa M, Bussière B, Chapuis RP (2003) A model to predict the water retention curve from basic geotechnical properties. Canad Geotech J 40(6): 1104-1122

Bain JG, Mayer KU, Blowes DW, Frind EO, Molson JW, Kahnt R, Jenk U (2001) Modeling the closure-related geochemical evolution of groundwater at a former uranium mine. J Contam Hydrol 52 (1-4): 109-135

Barbour ML, Hendry J (2002) In situ measurements and monitoring for rock wastes, Proc, Symp on Mines and the Environment, Rouyn-Noranda, Canad Inst of Mining & Metallurgy, Montreal, Canada, on CD-ROM

Bussière B (1999) Étude du comportement hydrique de couverture avec effets de barrière capillaire inclinées à l'aide de modélisations physiques et numériques. PhD Thesis, École Polytechnique de Montréal, Canada, 354 pp

Bussière B, Apithy SA, Aubertin M, Chapuis RP (2003a) Diversion capacity of sloping covers with capillary barrier effects. Proc, 56th Annual Canadian Geotechnical Conf, Winnipeg, Manitoba, Sept 29 – Oct 1, 2003, on CD-ROM

Bussière B, Aubertin M, Chapuis R (2003b) The behaviour of inclined covers used as oxygen barriers. Canad Geotech J 40(3): 512-535

Bussière B, Aubertin M, Chapuis R (2002) A lab set-up to evaluate the hydraulic behaviour of inclined capillary barriers. In: Phillips, Guo, Popescu (eds), Proc, Physical Modelling in Geotechniques: ICPMG '02, AA Balkema Publ, ISBN 90 5809 389 1, p 391-396

Campos D, Chouteau M, Aubertin M, Bussière B (2003) Using geophysical methods to image the internal structure of mine waste rock piles. Proc, EEGS Conf, Prague (on CD-ROM)

Celia MA, Bouloutas ET, Zarba RL (1990) A general mass-conservative numerical solution for the unsaturated flow equation. Water Resour Res 26: 1483-1496

Chapuis RP, Chenaf DC, Bussière B, Aubertin M, Crespo R (2001) A user's approach to assess numerical codes for saturated and unsaturated seepage conditions. Canad Geotech J 38(5): 1113-1126

Dagenais A-M, Aubertin M, Bussiere B, Cyr J, Fontaine R (2002) Ausculation et suivi du recouvrement multicouche construit au site minier Lorraine, Latulippe, Quebec. Proc, Symp on Mines and the Environment, Rouyn-Noranda, Canad Inst of Mining & Metallurgy, Montreal, Canada (on CD-ROM)

Eriksson N, Destouni G (1997) Combined effects of dissolution kinetics, secondary mineral precipitation and preferential flow on copper leaching from mining waste rock. Water Resour Res 33(3): 471-483

Fala O (2002) Étude des écoulements non saturés dans les haldes à stériles à l'aide de simulations numériques. Mémoire de maîtrise (MScA, unpublished), Génie Minéral, Dépt CGM, École polytechnique de Montréal, Canada, 292 pp

Fala O, Aubertin M, Bussière B, Chapuis RP (2001) Modélisation numérique des écoulements non saturés et théorie des similitudes. Proc, 54th Canadian Geotechnical Conf, Calgary, Canad Geotech Soc, p 1132-1139

Fala O, Aubertin M, Molson JW, Bussière B, Wilson GW, Chapuis R, Martin V (2003) Numerical modelling of unsaturated flow in uniform and heterogeneous waste rock piles. In: Farrell T, Taylor G (eds), 6th International Conf on Acid Rock Drainage (ICARD), Australasian Inst of Mining and Metallurgy, Cairns, Australia, Publ Series 3/2003, p 895-902

Gamache-Rochette A (2003) Water flow characterization in unsaturated rock waste piles using in situ hydrogeological tests. MSc Thesis (in French), Ecole Polytechnique, Montreal, Canada, 162 pp

Gerke HH, Molson JW, Frind EO (1998) Modelling the effect of chemical heterogeneity on acidification and solute leaching in overburden mine spoils. J Hydrol 209: 166-185

Kline SJ (1965) Similitude and Approximation Theory. McGraw-Hill Inc, NY, New York, USA

Lefebvre R, Hockley D, Smolensky J, Gélinas P (2001a) Multiphase transfer process in waste rock piles producing acid mine drainage. 1. Conceptual model and system characterization. J Contaminant Hydrol 52: 137-164

Lefebvre R, Hockley D, Smolensky J, Lamontagne A (2001b) Multiphase transfer process in waste rock piles producing acid mine drainage. 2. Applications of numerical simulation. J Contaminant Hydrol 52: 165-186

Li M (2000) Unsaturated flow and transport observations in large waste rock columns. Proc, 5th ICARD, Denver, SME, p 247-256

Martin V (2004) Étude des Propriétés non Saturées des Stériles Miniers, MSc Thesis (in French), École Polytechnique, Montreal, Canada, 247 pp

Mayer KU, Frind EO, Blowes DW (2002) Multicomponent reactive transport modeling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. Water Resour Res 38(9) 13:1-21

Mbonimpa M, Aubertin M, Chapuis RP, Bussière B (2002) Practical pedotransfer functions for estimating the saturated hydraulic conductivity. Geotech Geol Eng 20(3): 235-259

Mbonimpa M, Aubertin M, Aachib M, Bussière B (2003) Diffusion and consumption of oxygen in unsaturated cover materials. Canad Geotech J 40(5): 916-932

McCarter MK (1990) Design and operating considerations for mine waste embankments. In: Kennedy BA (ed), Surface Mining (2nd edit), SME, p 890-899

Molson JW, Fala O, Aubertin M, Bussière B (2005) Numerical simulations of pyrite oxidation and acid mine drainage in unsaturated waste rock piles. J Contaminant Hydrol 78 (4): 343-371

Morin KA, Gerencher E, Jones CE, Konasewich DE (1991) Critical literature review of acid drainage from waste rock. MEND Report 1.11.1, CANMET, 175 pp

Morin KA, Hutt NM (1994) An empirical technique for predicting the chemistry of water seeping from mine-rock piles. USBM SP 06 A-94, p 12-19

Munson BR, Okiishi ThH, Young DF (1994) Fundamentals of Fluid Mechanics. Wiley, NY, New York, USA, 843 pp

Nichol C (2002) Transient Flow and Transport in Unsaturated Heterogeneous Media: Field Experiments in Mine Waste Rock. PhD Thesis, Univ of British Columbia, 391 pp

Nichol C, Smith L, Beckie R (2003) Time domain reflectrometry measurements of water content in coarse waste rock. Canad Geotech J 40(1): 137-148

Nicholson RV, Gillham RW, Cherry JA, Reardon EJ (1989) Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canad Geotech J 26: 1-8

Noël MM, Ritchie AIM (1999) Some physical properties of water transport in waste rock material. Proc, 7th IMWA Symp, Sevilla, Spain, p 449-454

Oldenburg CM, Pruess K (1993) On numerical modelling of capillary barriers. Water Resour Res, 29(4): 1045-1056

Poulin R, Hadjigeorgiou J, Lawrence RW (1996) Layered mine waste co-mingling for mitigation of acid rock drainage. Trans Inst Min Metall 105: A55-A62

Price WA (2003) The mitigation of acid rock drainage: Four case studies from British Columbia. Proc, Sudbury 2003, CD-ROM, 1121 pp

Ricard JF, Aubertin M, Firlotte FW, Knapp R, McMullen J, Julien M (1997) Design and construction of a dry cover made of tailings for the closure of Les Terrains Aurifères Site, Malartic, Quebec, Canada. Proc, 4th ICARD, Vancouver, Canada, May 31-June 6, p 1517-1525

Richards LA (1931) Capillary conduction of liquids through porous media. J of Physics 1: 318-333

Ritchie AIM (1994) Sulphide oxidation mechanisms: Controls and rates of oxygen transport. In: Jambor JL, Blowes DW (eds), Ch 8: Short Course Vol 31, Mineralogical Assoc of Canada, p 201-245

Ritchie AIM (2003) Oxidation and gas transport in piles of sulphidic material. In: Jambor JL, Blowes, DW, Ritchie AIM (eds) Environmental Aspects of Mine Wastes, Ch 4, Short Course Vol 31, Mineralogical Assoc of Canada, p 73-94

Ross B (1990) The diversion capacity of capillary barriers. Water Resour Res 26: 2625-2629

Simunek, J, Sejna M, van Genuchten ThM, (1999) The HYDRUS-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, *IGWMC - TPS - 53,* International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, USA, 251 pp

Simunek, J, Vogel T, van Genuchten ThM (1994) The SWMS_2D Code for Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media. Version 1.21, Research Report 132, US Salinity Laboratory, USDA, ARS, Riverside, CA, USA, 210 pp

Smith L, Lòpez DL, Beckie R, Dawson R, Price W (1995) Hydrogeology of Waste Rock Dumps. Natural Resources Canada Contract 23440-4-1317/01-SQ, MEND Report PA-1, Natural Resources Canada

Smith L, Beckie R (2003) Hydrologic and geochemical transport processes in mine waste rock. In: Jambor JL, Blowes DW, Ritchie AIM (eds) Environmental Aspects of Mine Wastes, Ch 3, Short Course Vol 31, Mineralogical Assoc of Canada, p 51-72

van Genuchten, MTh (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Soc America J 44: 892-898

Wels C, Lefebvre R, Robertson AM (2003) An overview of prediction and control of air flow in acid-generating waste rock dumps: In: Farrell T, Taylor G (eds), Proc, 6th International Conf on Acid Rock Drainage, Australasian Inst of Mining and Metallurgy, Cairns, Australia, Publ Series 3/2003, p 639-650

Wilson GW (2003) The design and performance of mine-waste cover systems. In: Jambor JL, Blowes, DW, Ritchie AIM (eds) Environmental Aspects of Mine Wastes, Ch 18, Short Course Vol 31, Mineralogical Assoc of Canada, p 377-384

Wilson JA, Wilson GW, Fredlund DG (2000) Numerical modeling of vertical and inclined waste rock layers. Proc, 5th ICARD, SME, Denver, p 257-266

Woyshner MR, Yanful EK (1995) Modelling and field measurements of water percolation through an experimental soil cover on mine tailings. Canad Geotech J 32: 601-609

Zhan G (2000) Experimental and theoretical studies on leach pad hydraulics and transport behavior during rinsing. PhD Thesis (unpublished), Univ of Nevada, Reno, USA, 180 pp

Zhan G, Aubertin M, Mayer A, Burke K, McMullen J (2001) Capillary cover design for leach pad closure. SME Transaction 310: 104-110

Submitted Feb. 27, 2005; accepted Sept. 15, 2005