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TECHNICAL ARTICLE

Effect of Dense Material Layers on Unsaturated Water Flow Inside a Large Waste Rock Pile: A Numerical Investigation

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Abstract The construction method used to build waste rock piles influences their internal structure. Commonly used methods typically lead to the creation of compacted material layers within otherwise loose, coarse-grained waste rock. These dense layers, which typically have a finer grain size, affect the movement and distribution of water inside the pile. Long-term numerical simulations of unsaturated flow in a large pile were conducted to investigate the effect of such layers. The simulations led to various observations that provide a better understanding of the hydrogeological behaviour of the modeled pile (based on an actual case). The results show how water distribution and seepage within the pile are influenced by the presence of these layers. Other factors, including the magnitude of precipitation (or recharge) and pile size, were also investigated. This article presents the main results of the simulations, with some comments on their practical implications for pile design.

Keywords Capillary barrier · Hydrogeological behaviour · Internal layers · Modeling

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Introduction

The environmental response of a waste rock pile depends on various factors including the mineralogical composition of the waste rock, grain size distribution, and porosity. Reactive materials in waste rock can produce acid mine drainage (AMD) or contaminated neutral drainage (CND) along the infiltrating water flow path (e.g. Bussière et al. 2005, 2011; Fala et al. 2006, 2012; Lefebvre et al. 2001; Molson et al. 2005; Ritchie 2003; Sracek et al. 2004; Stantec Consulting Ltd 2004), which can negatively affect the surrounding ecosystems. There is thus a need to apply efficient measures to prevent or control such undesirable effects. The first line of defence begins with the pile design, which should aim at limiting water infiltration and flow within the reactive waste rock (e.g. Aubertin 2013; Aubertin et al. 2002b, 2005, 2008; Dawood et al. 2011; Wels et al. 2003; Williams and Rohde 2007; Williams et al. 2008). This can be accomplished by adopting suitable construction methods. Typical construction methods, with heavy equipment, often lead to the creation of sub-horizontal layers of compacted material, especially in piles located on relatively flat surfaces (Anterrieu et al. 2010). These compacted layers can significantly affect the hydrogeological response of a pile (e.g. Aubertin et al. 2002a, b; Fala 2008; Fala et al. 2003, 2005, 2006; Martin et al. 2005).

The distribution and movement of water through a waste rock pile are, however, difficult to measure, interpret, and predict. The large spatial and temporal variations observed for the grain size, porosity, and in situ degree of saturation (or volumetric water content) of the waste rock make this a complex problem. Nonetheless, recent developments with laboratory and field tests, in situ monitoring, and numerical modeling tools have led to a better understanding of the main phenomena that affect the hydrogeological and

Table 1 Simulated scenarios

Description	Simulation	Figure	Pile size	Main material	Fine-grained material	Number of layers	Layer inclination	Precipitation regime
Base case	S1	4	Large	GRV	–	–	–	P1-E
Effect of precipitation	S2	5	Large	GRV	–	–	–	P2-E
Effect of number of layers	S3	6	Large	GRV	SBL	1	Horizontal	P1-E
	S4	7	Large	GRV	SBL	2	Horizontal	P1-E
	S5	8	Large	GRV	SBL	4	Horizontal	P1-E
Effect of inclination angle	S6	9	Large	GRV	SBL	2	5 %	P1-E
	S7	10	Large	GRV	SBL	2	10 %	P1-E
Effect of material properties	S8	11	Large	GRV	SLT	2	5 %	P1-E
	S9	12	Large	GRV	SLT	2	10 %	P1-E
Effect of pile size	S10	13	Small	GRV	SBL	2	Horizontal	P1-E
	S11	14	Small	GRV	SBL	2	5 %	P1-E

E evaporation, *P1* first cycle of precipitation, *P2* second cycle of precipitation (E, P1, and P2 are shown in Fig. 2), *GRV* gravelly, *SBL* sandy, and *SLT* silty materials

geochemical behaviour of waste rock piles, including the effects of localized flow and capillary barrier effects due, respectively, to the presence of macropores and horizontal (or inclined) compacted layers (e.g. Aubertin et al. 2002b, 2005, 2008; Bussière et al. 2011; Dawood et al. 2011; Smith and Beckie 2003; Smith et al. 1995; Wilson et al. 2000). In this regard, capillary barriers, induced when compacted material layers are created above loose coarse-grained waste rock, constitute an important component that affects water flow in an unsaturated pile. When properly applied, such capillary barriers can be used to control the movement of water and air through piles (e.g. Fala et al. 2003, 2005, 2006; Lefebvre et al. 2001; Molson et al. 2005). Capillary barrier effects can also be used to design cover systems that limit water infiltration from the surface to the inside of piles (e.g. Aubertin et al. 2006, 2009; Martin et al. 2005; Zhan et al. 2001).

In this investigation, the finite element code HYDRUS-2D (Šimunek et al. 1999) was used to assess the potential effects of internal features (mainly compacted material layers) on the long-term hydrogeological response of a large waste rock pile having some of the characteristics of an existing pile. Different scenarios were simulated to assess the potential impact of these features (Table 1). Simulation S1 constitutes the base case with a pile made of a single material (gravelly waste rock, GRV); simulation S2 illustrates the effect of the precipitation regime (i.e. recharge); simulations S3, S4, and S5 illustrate the effect of horizontal layers; simulations S6 and S7 show the effect of inclined layers; simulations S8 and S9 illustrate the effects of different material properties; and the last two, S10 and S11, investigate the influence of pile size on water distribution and movement. The results from these simulations help clarify the effects of these factors on water movement inside such a waste rock pile.

Characteristics of the Conceptual Model

Analysing the hydrogeological behaviour of a waste rock pile can be a challenge. Numerical simulations can be quite helpful in identifying key factors. Various codes can be used for modeling the unsaturated flow within piles. For this investigation, the authors used the finite element code HYDRUS-2D (Šimunek et al. 1999), which has also been used for the analysis of smaller piles (Fala et al. 2003, 2005, 2006, 2008, 2012). This code uses Richards' (1931) unsaturated flow equation, which can be expressed as follows (for two-dimensional Cartesian coordinates, x, z):

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

In this equation, ψ is the water pressure (expressed as a head, L), θ is the volumetric water content (−), t is time (T), and k_x and k_z (L/T) are the pressure-dependent hydraulic conductivities in the horizontal and vertical directions, respectively.

The two-dimensional waste rock pile model, which is loosely based on an actual field case, has a base width of 260 m and a height of 109 m (Fig. 1a). The surface of the pile is open to atmospheric conditions. The base of the pile consists of two zones: the first zone (on the right hand side of Fig. 1a) is made of impervious rock, and the second (on the left) is under water. The impervious vertical boundary condition imposed on the right hand side of the model corresponds to a line of separation for the flow net inside the pile. The residual water content θ_r is applied as the initial condition in each simulation.

Figure 1b shows a smaller pile (having a base width of 65 m and a height of 27.25 m) that is analyzed in the latter part of this paper; the same initial and boundary conditions were used for this small pile.

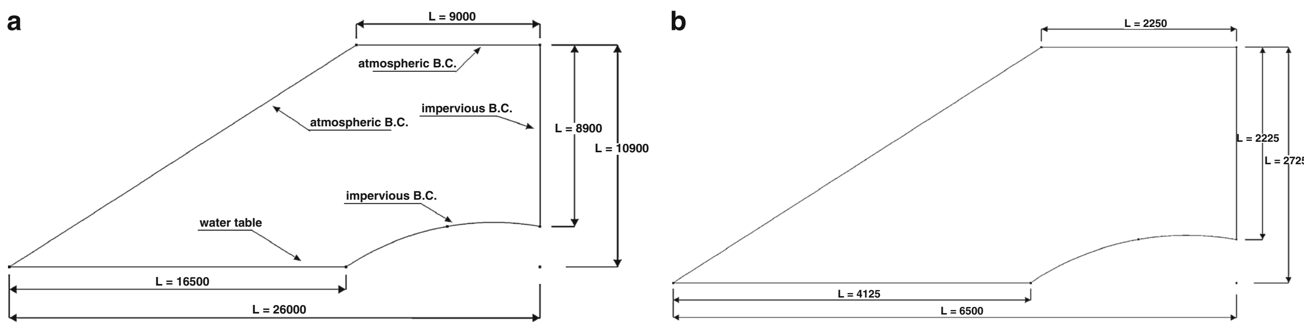

Fig. 1 **a** Geometry and boundary conditions (B.C.) for the large waste rock pile, **b** geometry and boundary conditions for the small waste rock pile, (an example of a finite element mesh provided as a supplemental Fig. I); all dimensions are in cm

The finite element mesh, made of triangular elements, was generated using HYDRUS-2D mesh generator tools. Figure I is published as a supplemental file, which means that it can be viewed and downloaded (for free by all journal subscribers) in the online version of this paper; it shows an example of the mesh used for the simulations. The number of elements varies among simulations, depending on the number of compacted layers (as the elements in these layers are smaller than in the rest of the pile), their inclination angle, and the size of the pile. Typical calculation times for these simulations varied between 2 and 14 days on a HP Compaq computer (2.7 GHz AMD processor and 2 gigabytes of RAM). More details about the numerical parameters and conditions used in this study were presented in an internal technical report (Dawood and Aubertin 2012).

Three materials were used to represent different fractions (or types) of waste rock inside the pile. These can be classified as very coarse (gravelly-GRV), coarse (sandy-SBL), and fine (silty-SLT). The properties of these materials were obtained from laboratory and field tests conducted in recent years (Aubertin et al. 2005, 2008; Bussière et al. 2011). The hydrogeological parameters used in the simulations (Table 2) are based on the van Genuchten (1980) model for the water retention curve (Eq. (2)), and on the Mualem (1976) formulation for the unsaturated hydraulic function (Eq. (3)); the corresponding equations can be expressed as follows:

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

$$k = k_s \theta_e^{0.5} \left[1 - \left(1 - \theta_e^{1/m_v}\right)^{m_v}\right]^2 \quad (3)$$

In these equations, θ_e is the effective volumetric water content; θ_s is the saturated volumetric water content (it is equal to the porosity, n); θ_r is the residual volumetric water content; α_v, m_v, and n_v (with $m_v = 1 - 1/n_v$) are the van Genuchten (1980) model parameters; k is the unsaturated hydraulic conductivity (L/T), which depends on the water content (or suction), and; k_s is the saturated hydraulic conductivity.

The values of the model parameters (Table 2), which are based on experimental results (as mentioned above), indicate that there are large differences in the hydrogeological properties of the three materials. These differences are illustrated in Fig. II (provided as a supplemental file), which shows the water retention curves ($\theta - \psi$) and hydraulic conductivity functions ($k - \psi$) for the three materials, respectively. On this figure, the saturated hydraulic conductivity (at $\psi = 0$) is decreasing when going from the coarse GRV material to the finer, sandy and silty materials. However, because finer grained materials tend to retain more water at a given suction (as seen on the water retention curves), the unsaturated hydraulic conductivity of the GRV rapidly decreases as suction is increased, followed by the SBL. Hence, under unsaturated conditions, the value of k is typically larger for finer grained materials (e.g. Fredlund and Rahardjo 1993; Fredlund et al. 2012; Lu and Likos 2004).

The climatic data (i.e. cycles of precipitation–evaporation) used in this study were based on the monthly average values measured at the Latulipe, Quebec (Canada) monitoring station (P1-E), and (for the more humid regime) at Addis-Ababa, in Ethiopia (P2-E). The evaporation cycle is embedded into the recharge cycle imposed on the surface boundary of the pile; only the net recharge results are included in the calculations (i.e. there is no evaporation flux). The Ethiopia case was used here to increase the recharge rate and assess its effect on water flow and distribution. The monthly distributions are presented in Fig. 2.

It should be noted that the numerical work performed here assumes Darcian flow in the pile. Turbulent flow has been reported for some waste rock piles that contain poorly graded material with an open structure, which can lead to preferred flow in relatively large voids (e.g. Morin et al. 1991; Smith and Beckie 2003). However, the authors' work on piles from hard rock mines has been conducted on relatively well-graded materials with a sizable sandy

Table 2 The Mualem (1976)—van Genuchten (1980) model parameters for the materials used in the numerical simulations performed with HYDRUS-2D

Material	θ_r	θ_s	α_v (cm^{-1})	n_v	k_s (cm/s)
GRV	0	0.39	149.6	1.45	4.7×10^{-1}
SBL	0.01	0.29	0.03	3.72	5.1×10^{-2}
SLT	0.034	0.46	0.016	1.37	6.9×10^{-5}

θ_r: residual volumetric water content; θ_s: saturated volumetric water content; α_v and n_v are van Genucheten parameters; k_s: saturated hydraulic conductivity

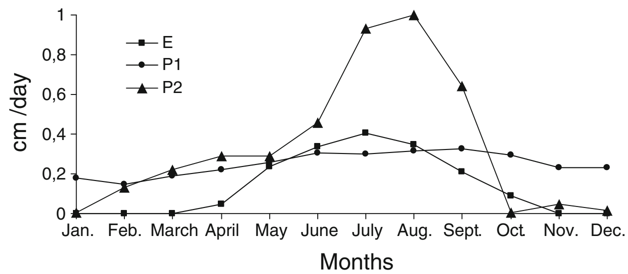

Fig. 2 Cycles of Precipitation–evaporation used in the simulations; *P1* precepitation values at Latulipe, *E* evaporation values at Latulipe, *P2* precepitation values at Addis-Ababa

fraction (e.g. Anterrieu et al. 2010; Aubertin et al. 2005, 2008; Martin et al. 2005). Turbulent flow is deemed absent under these conditions, at least in the central core of the pile; this aspect is further addressed below in the Discussion.

Simulations Results

Base Cases

The gravelly material was used in simulation S1 to model a fully constructed, homogeneous pile over a period of 10 years. Results at the end of December of the 10th year are presented in Fig. 3, which shows the contour distribution of the volumetric water content θ (Fig. 3a) and the vertical water velocity (Fig. 3b). $\theta = 0.011$ at the beginning of the simulation; this initial value was imposed to control numerical problems, and should not affect the long response of the pile [as shown by Fala et al. (2006)]. After 10 years, the values of θ are less than 0.1. Water has moved deeper but the wetting front has not yet reached the base of the pile near its central core (above the impervious rock). Near the inclined surface of the pile (left hand side of Fig. 3), the infiltrating water has reached the water table (as expected) due to the shorter vertical distance. Also, the volumetric water content close to the surface is typically higher than in the rest of the pile due to the direct exposure to infiltrating water (mainly autumn precipitation).

Figure 3b shows that water velocity varies between 0 and 0.035 cm/h and that it follows the distribution of the volumetric water content (k increases with θ). These results indicate that the infiltrating water front in the homogenous pile has traveled about 65 m near the center of the pile over 10 years. Additional results (Dawood and Aubertin 2012) indicate that the values of θ and v evolve during the year, and that the pattern is repeated monthly each year (for the same recharge cycle).

Additional calculations were also conducted for a similar pile made with SBL material (instead of the GRV). The simulation results, also shown in Dawood and Aubertin (2012), are fairly similar to those in Fig. 3, except that the θ values in the SBL were smaller than in the GRV, due to the larger porosity (Table 2) and lower unsaturated hydraulic conductivity (supplemental Fig. II) of the gravelly material. Also, the main wetting front reaches the base (near the center of the pile) much faster, i.e. after 6 years, for the SBL material (which is more pervious than the GRV under most unsaturated conditions—see supplemental Fig. II).

Effect of Recharge Rate

A different precipitation–evaporation cycle (Fig. 2) was used to assess the influence of surface recharge on the movement and distribution of water through the homogenous (GRV) waste rock pile. In simulation S2, the precipitation cycle of Latulipe was replaced by that of Addis-Ababa (which increases the recharge by about 35 %). The results of simulation S2 are shown in Fig. 4. It is seen on Fig. 4a that the volumetric water content is typically close to 0.1 down to a depth 87 m, beyond which it drops to almost zero. These results indicate that there is no significant difference in the values of θ for cases S1 and S2, except for the depth of the wetting front inside the pile (i.e. 89 m for S2 vs. 65 m for S1). Water velocity contours presented in Fig. 4b show that v remains below 0.05 cm/h. The higher water velocity observed for S2 is mainly due to the increased hydraulic conductivity (k) associated with higher volumetric water content (θ). Larger precipitation events can thus be expected to transport contaminants more quickly to the groundwater system in such a homogenous pile, even under unsaturated conditions.

Effect of Fine Grained Material Layers

Previous calculations have shown that compacted layers, made with denser and finer materials, modify the transient flow of water inside a small (25 m high) waste rock pile (Fala et al. 2003, 2005). This aspect is investigated here for the much larger pile shown in Fig. 1a. It should be noted that the layers added on top of and (in some cases) inside the pile have an irregular interface with the coarser

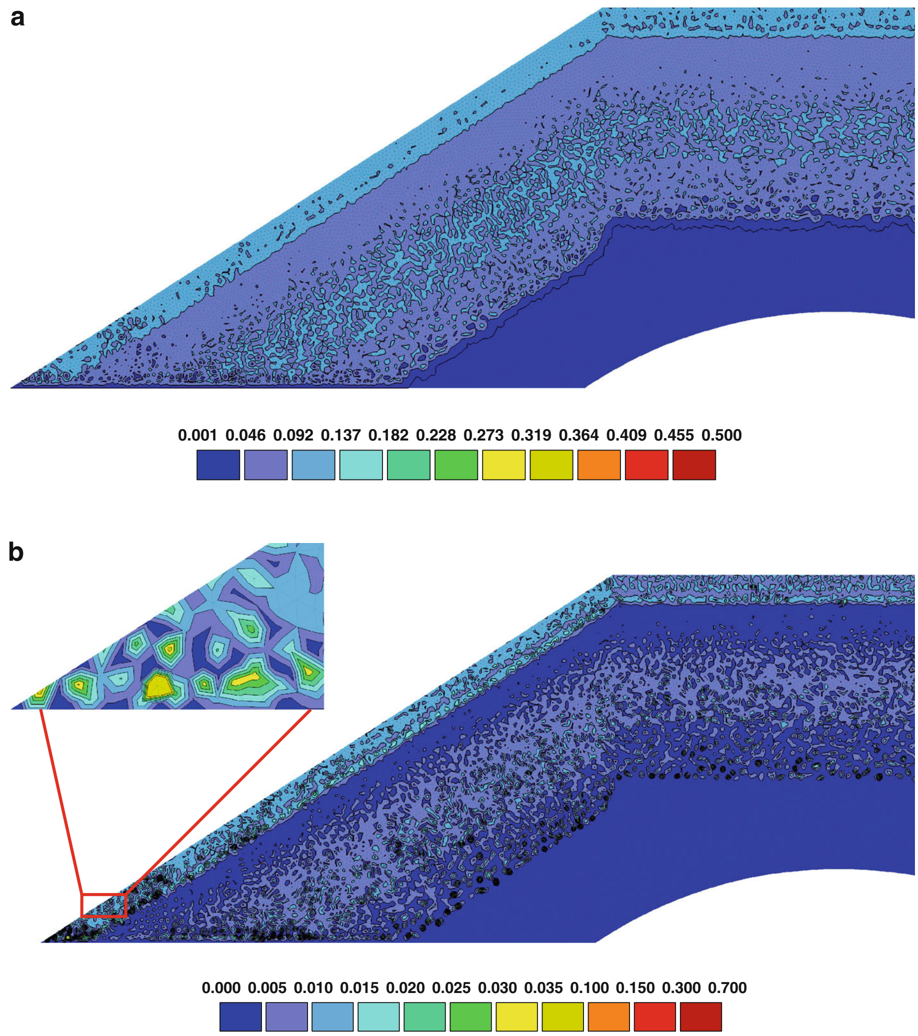

Fig. 3 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S1 (GRV) at the end of December of the 10th year

material beneath; this non-planar geometry within the finite element mesh is considered more realistic for the compacted layers, based on field observations in trenches (e.g. Anterrieu et al. 2010; Martin et al. 2005). This geometry can favour water accumulation in local troughs that exist along the contact between the finer and coarser materials, which can then lead to more pronounced localized flow beneath these layers (Fala et al. 2005, 2006), as will be shown below.

Number of Layers

A layer of sandy material (SBL), 0.5 m thick, was added on top of the pile (made of GRV material) in simulation S3. This horizontal layer represents the effect of surface compaction by the heavy equipment (Aubertin et al. 2002b, 2005). The calculations were conducted with the same initial and boundary conditions as used above (Fig. 1; Tables 1, 2). Figure III is provided as a supplemental file in the online version of this paper. Figure IIIa shows the distribution of the volumetric water contents (θ) at the end of December of the 10th year. It is seen that the θ values are higher in the sand layer, due in part to the creation of a capillary barrier effect between the finer and coarser materials near the top of the pile (e.g. Aubertin et al. 2009). However, Fig. IIIa also shows that this sandy layer had a limited effect of on water transport inside the pile itself. The horizontal sand layer causes a local accumulation of water that eventually escapes downward, causing localised flow zones in the pile. The θ value in the sandy layer (90 m long and 0.5 m thick) varied between 0.05 (top) and 0.25 (base), and between 0.01 and 0.1 in the rest of the pile. Figure IIIb shows that the water velocity in the sandy layer ranged between 0.005 and 0.10 cm/h, and between 0 and 0.03 cm/h elsewhere. Comparing the base case (S1) with simulation S3 (with a sand layer) indicates that some of the water reached the base of the pile faster in the latter case due to the localized (preferential) flow zones.

Two horizontal sandy material layers were added to the pile in simulation S4: one on top (90 m long and 0.5 m

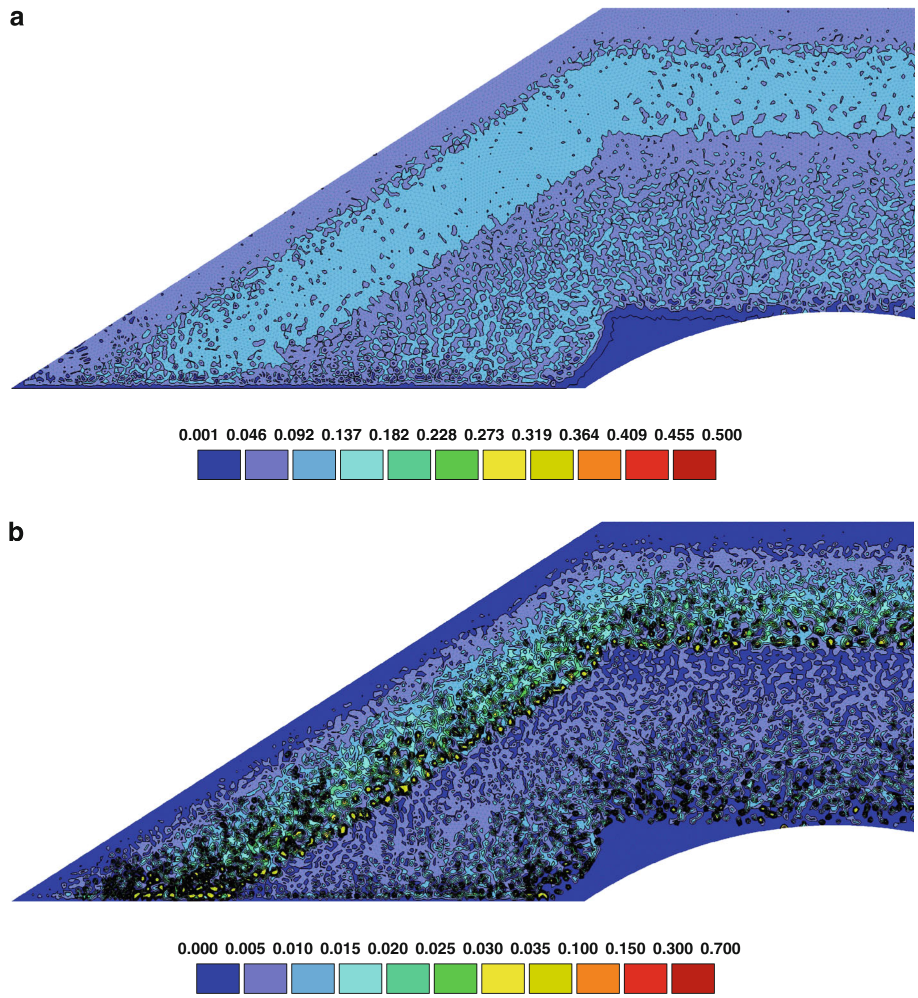

Fig. 4 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S2 (GRV, precipitation cycle P2-E) at the end of December of the 10th year

thick), and one at mid-height (185 m long, with the same thickness) to represent the effect of a previously compacted surface. The results of the simulation after 10 years are shown in Fig. 5a and b. The results of simulation S4 show the creation of capillary barrier effects due to the different hydraulic properties of the SBL and GRV materials, producing an increased number of localized flow paths. The volumetric water content in the upper sand layer varied between 0.04 and 0.15 and between 0.06 and 0.18 in the mid-height sand layer, while the value of θ in the rest of the pile stayed below 0.12 (Fig. 5a). Water velocities in the top sandy layer varied between 0.005 cm/h (near the upper surface of the layer) and 0.1 cm/h (near the lower surface of the layer). For the mid-height layer, water velocities ranged between 0 and 0.07 cm/h. Velocity remained under 0.035 cm/h in the rest of the pile.

Four horizontal sandy layers (90, 124, 159, and 194 m long, with the same 0.5 m thickness) were added at regular intervals in the pile in simulation S5. The volumetric water content distribution within the four layers also indicated the presence of capillary barriers effects (see Supplemental Fig. IVa). The volumetric water content in the top and second sandy layers varied between 0.04 and 0.15. In the third layer, θ varied between 0.04 and 0.17; in the fourth layer, the value of θ varied between 0.06 and 0.2; in the rest of the pile, θ ranged between 0.01 and 0.12. Supplemental Fig. IVb shows that vertical velocity at the end of December of the 10th year varied between 0 and 0.07 cm/h for the entire pile (including the SBL material layers).

Comparing the results from simulations S3, S4, and S5 (Figs. III, IV, 5) with the base case (S1, Fig. 3, homogenous pile) indicates that water tends to accumulate inside the compacted layers and then move down along preferential flow paths created below the SBL-GRV interfaces. The horizontal layers tend to cause a more rapid flow of water deeper inside the pile. The same observations were made following short term (1 year) simulations of water flow inside a smaller pile with two horizontal layers (Fala et al. 2003, 2005). As such layers are known to exist in actual waste rock piles (Anterrieu et al. 2010; Dawood et al. 2011), these results suggest that water flow in piles is largely influenced by internal structure, with water moving

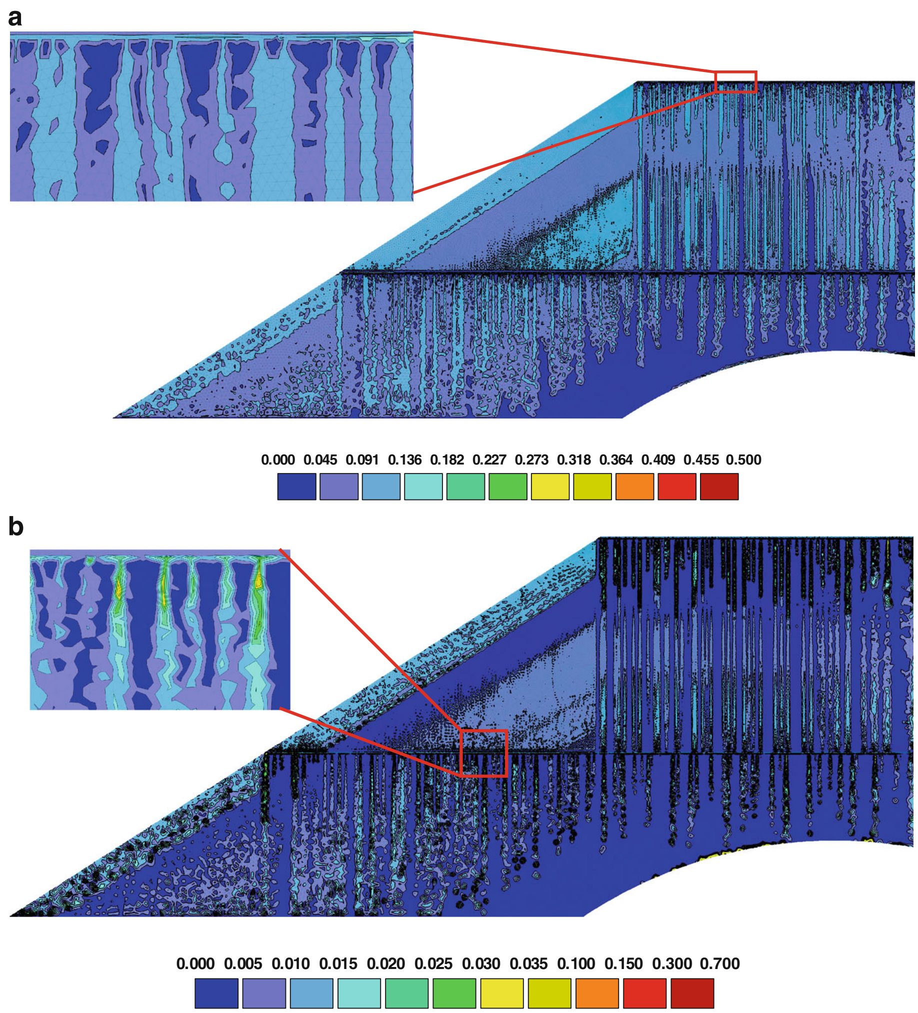

Fig. 5 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S4 at the end of December of the 10th year; two sand layers are added on *top* and at mid-height of the pile

deeper and faster due to such layers than in idealised homogeneous piles.

Inclined Layers

Earlier simulations results (Fala et al. 2003, 2005, 2006) showed that fine-grained (sandy) material layers can reduce water flow deep inside a relatively small pile when these layers are inclined outward. In the next simulations (S6 and S7), two sandy layers were introduced with inclinations of 5 and 10 % to assess their effect on water movement through the large pile.

Slope of 5 %

Two sandy layers, located on top and at mid-height of the pile, were inclined at 5 % outward (simulation S6). The results after 10 years are shown in Fig. 6a and b. The volumetric water content in the top layer varied between 0.04 and 0.27 and between 0.04 and 0.24 in the mid-height layer, while it was less than 0.12 for the rest of the pile (Fig. 6a). The vertical velocity varied between 0.001 and 0.7 cm/h on the top layer and between 0.001 and 0.3 cm/h for the second layer, while it was under 0.05 cm/h for the rest of the pile (Fig. 6b).

Slope of 10 %

Simulation S7 was conducted with sandy layers inclined at 10 % (the maximum angle that could be applied in the field). The results (Fig. 7a) indicates that the volumetric water content ranged between 0.04 and 0.12 in the top sand layer, between 0.04 and 0.16 in the second sand layer, and below 0.10 in the rest of the pile. Figure 7b shows that water velocity ranged between 0.001 and 0.05 cm/h in the top layer (near the upper and lower surfaces of the layer, respectively), between 0.001 and 0.14 cm/h in the second layer (again increasing with depth), and below 0.03 cm/h in the rest of the pile.

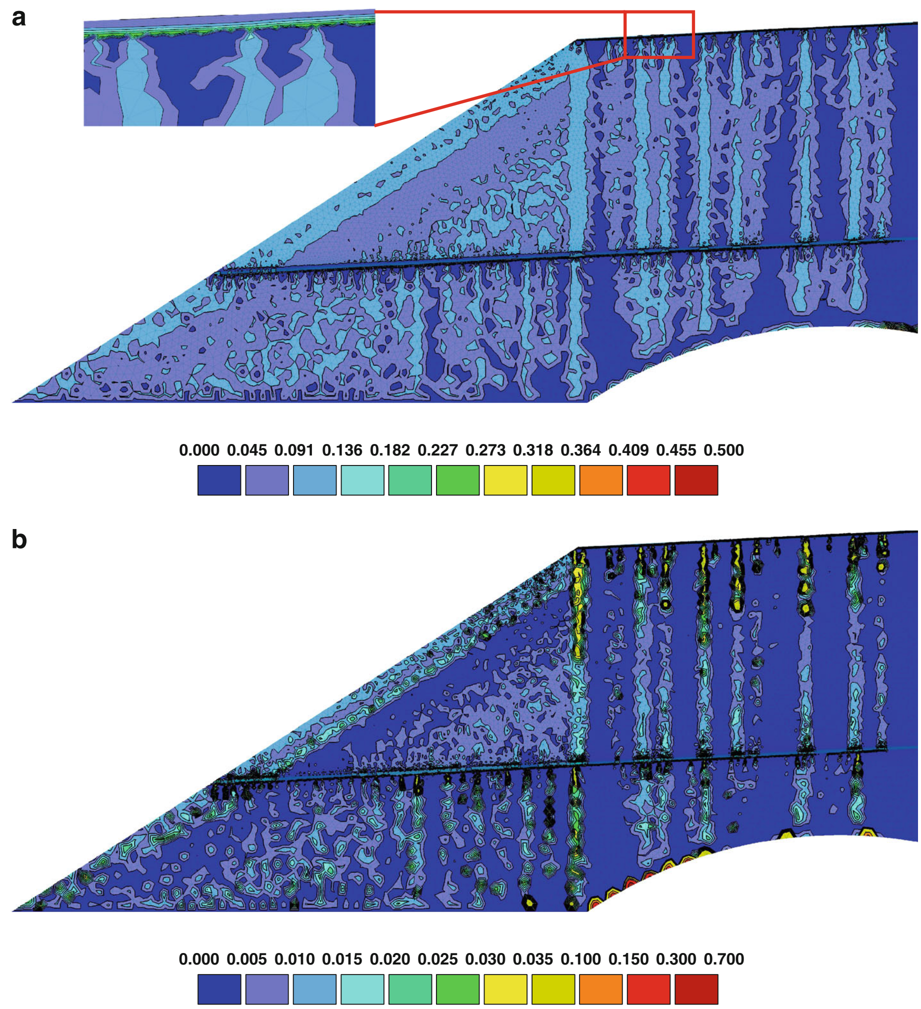

Fig. 6 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S6 at the end of December of the 10th year; the two sand layers added on *top* and at mid-height of the pile are inclined at 5 %

Effect of Inclined Layers

Supplemental Table 3 compares key results from the previous simulations. Comparing results from simulation S4 (Fig. 5, with two horizontal sandy layers) with those from simulation S6 indicates that the 5 % inclination of the two sandy layers tended to increase the volumetric water content at the base of the SBL layers, especially downslope (near the edge of the pile). Also, the water moved preferentially toward the external boundary (left hand side) of the pile within the sandy layers. These observations suggest that inclined layers can help control flow in piles by creating zones (in the core of the pile) where there is less water moving with a lower velocity. However, these results are less conclusive for this large pile (compared with the smaller pile studied by Fala et al. 2003, 2005, 2006). The diversion capacity of the SBL layers is further limited by the irregular geometry at the base of the layers (instead of an idealized, flat contact area).

Comparing the results from S6 with those from S7 shows that the θ value in the first (top) sandy layer inclined at 10 % is generally smaller than with a 5 % inclination. The same tendency is observed for the second sandy layer at mid-height. Comparing the results from S6 and S7 with those obtained from S4 (two horizontal SBL layers) also indicates that the inclination of the finer and denser material layers tends to increase water content and velocity in these layers, especially near the edge, hence favouring water flow towards the pile's external boundary. The inclined layers also create areas with less water content in the center of the pile, particularly in the case of a 10 % inclination. However, the irregular shape of the interfaces between the finer and coarser materials and the large spacing between the inclined layers limits the effects of these layers on water flow. These two factors need to be assessed further.

Properties of the Compacted Material Layers

In the next simulations, the sandy material SBL (used in simulations S4 to S7) was replaced with a finer grained (silty) material, in order to increase the contrast in hydraulic properties between the gravelly waste rock and

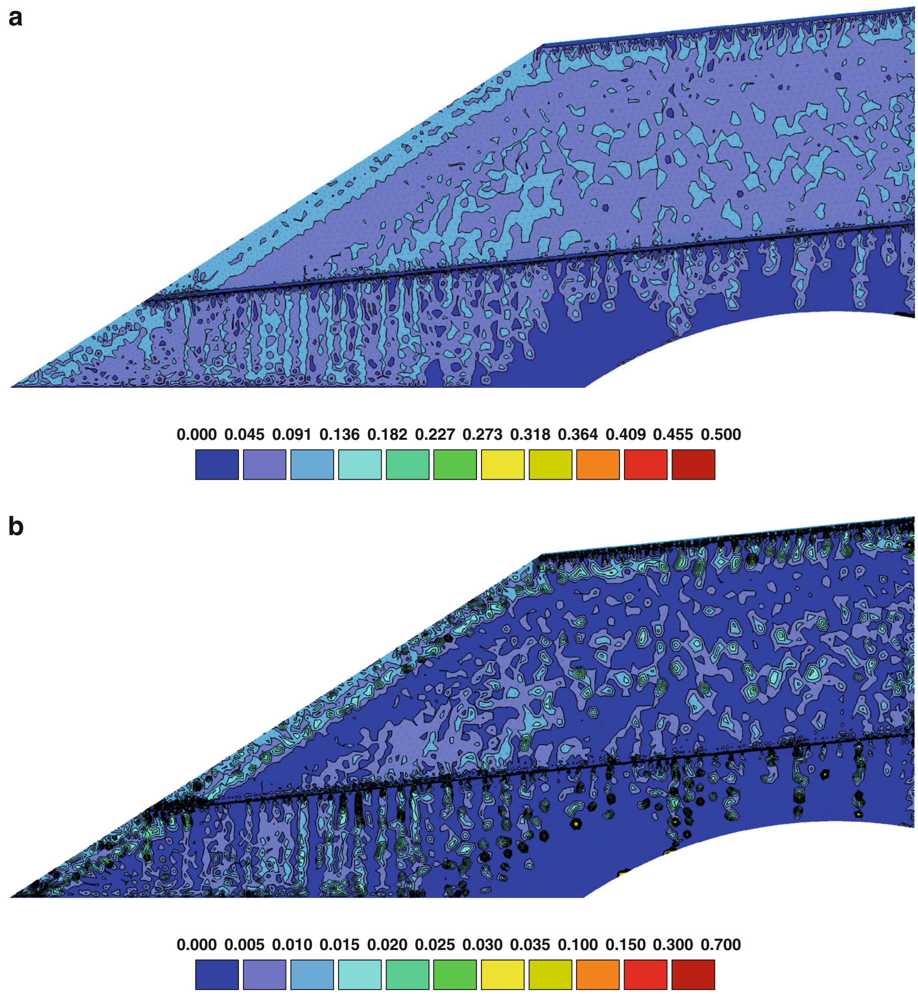

Fig. 7 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S7 at the end of December of the 10th year; the two sand layers added on *top* and at mid-height of the pile are inclined at 10 %

the compacted layers. The SLT layers, which could be made of tailings, had a lower saturated conductivity and a larger air entry value (AEV) than the SBL and GRV (Table 2). Figure 8a and b show the results of simulation S8 when two SLT layers (inclined at 5 %) were used. Comparing these results with those obtained from simulation S5 indicates that the volumetric water contents in the inclined layers increased from 0.27 (SBL layers) to 0.4 (SLT layers), while remaining around 0.12 in the rest of the pile for both cases. The maximum vertical velocity decreased from 0.7 cm/h (for S6) to 0.02 cm/h (for S8) in the top layer, from 0.3 cm/h (for S6) to 0.017 cm/h (for S8) for the mid-height layer, and about 0.014 cm/h in the rest of the pile, in both cases.

Two silty layers inclined at 10 % were included in simulation S9. The results (Supplemental Fig. Va) indicate that the volumetric water content in the silty layers was $\approx$ 0.4, while it was less than 0.12 in the rest of the pile. Supplemental Fig. Vb shows that vertical velocity in the two SLT layers varied between 0 and 0.035 cm/h, while it was less than 0.014 cm/h in the rest of the pile. The results also indicate that silty layers inclined at 10 % can be more efficient in creating zones inside the pile with less volumetric water content and velocity.

Effects of Pile Size

The size of the waste rock pile may affect its hydrogeological (and environmental) behaviour. Simulations were conducted on a smaller pile, 65 m in width and 27.25 m in height (a ratio 1:4 from the large pile, Fig. 1b) to assess the influence of pile size. Simulations S4 and S5 were repeated in simulations S10 and S11 using the smaller size with the same boundary and initial conditions. The effects of two horizontal sandy layers were about the same in the small and large pile (S4 and S10). Figures 5a and 9a show that the volumetric water content was similar in both cases (under 0.1 in the waste rock and above 0.1 in the SBL layers). Figures 6 and 10 show that inclining the two sandy layers at 5 % in the small pile (S11) produced θ and v values similar to those obtained with simulation S6 (for the large pile). Also, in the right hand side of the pile (Fig. 10a), close to

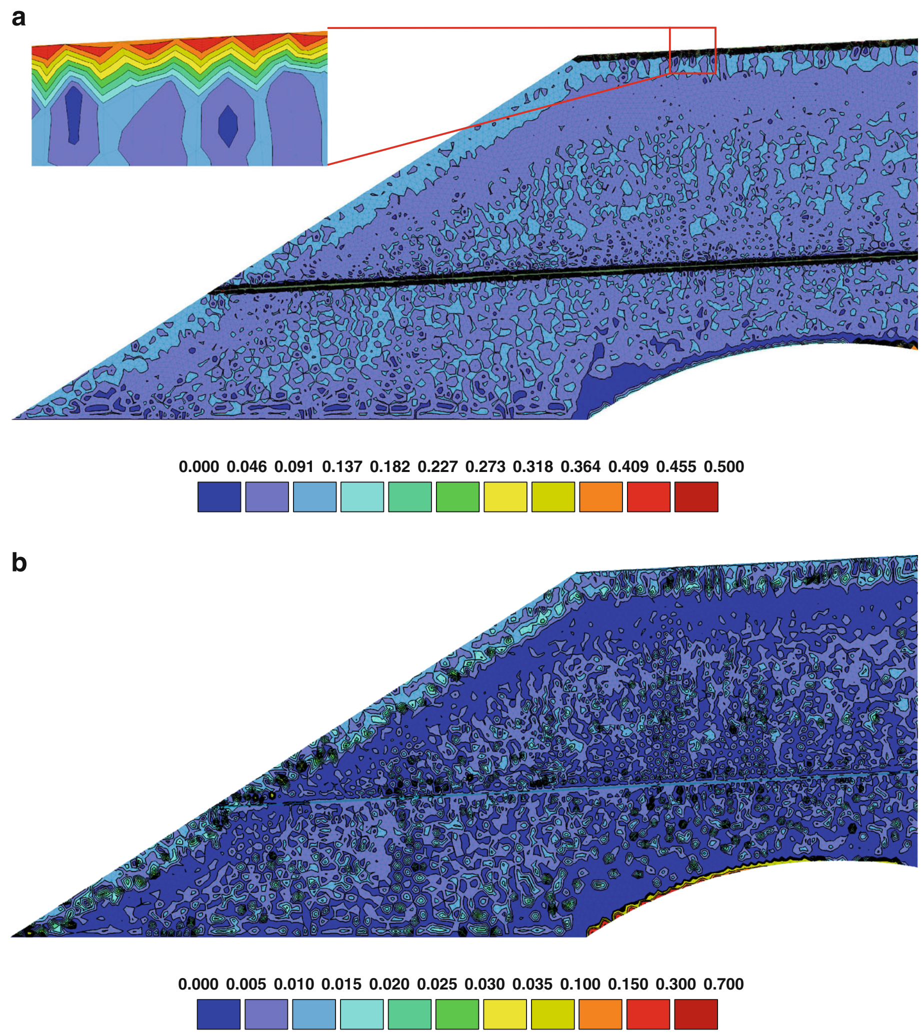

Fig. 8 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S8 at the end of December of the 10th year; the two silt layers added on *top* and at mid-height of the pile are inclined at 5 %

the imposed flow boundary, there are larger zones where θ is close to θ_r (i.e. indicating that water does not flow in these zones). Hence, the two sandy layers inclined at 5 % produce more favourable effects in the smaller pile by creating zones with limited or no water flow.

It is also seen that the wetting front in the smaller pile reached the base faster, leading to increased volumetric water content and water velocity near the bottom of the pile. The distribution of water inside the pile was different for the two cases. It can thus be concluded that the effect of the material layers on water flow inside a waste rock pile depends on its size, the inclination angle of layers, and their vertical spacing (when the same materials and boundary conditions are used).

Discussion

Results from several simulations illustrated the hydrogeological behaviour of a relatively large waste rock pile under different conditions, based on the movement and distribution of water inside an unsaturated pile after 10 years of the same recharge cycle. The results for the gravelly waste rock showed that the wetting front did not reach the base of the 109 m high pile after 10 years; in this case, the degree of saturation (S_r) remained very low (usually around 10 %), thus reducing the hydraulic conductivity of the waste rock in the entire pile. This would favour gas exchange with the atmosphere, in terms of air movement by advection, convection, and diffusion (Lefebvre et al. 2001; Molson et al. 2005). Under these conditions, air can easily travel inside the pile, providing the oxygen needed for oxidation reactions. The oxidation products would then be transported by the seepage throughout the pile.

The simulations that included horizontal layers of denser and finer materials in a gravelly waste rock pile (as observed in field studies; e.g. Anterrieu et al. 2010; Dawood et al. 2011) indicated that water flowed differently in various zones. Water tended to accumulate in the finer-grained material layers because of their higher water

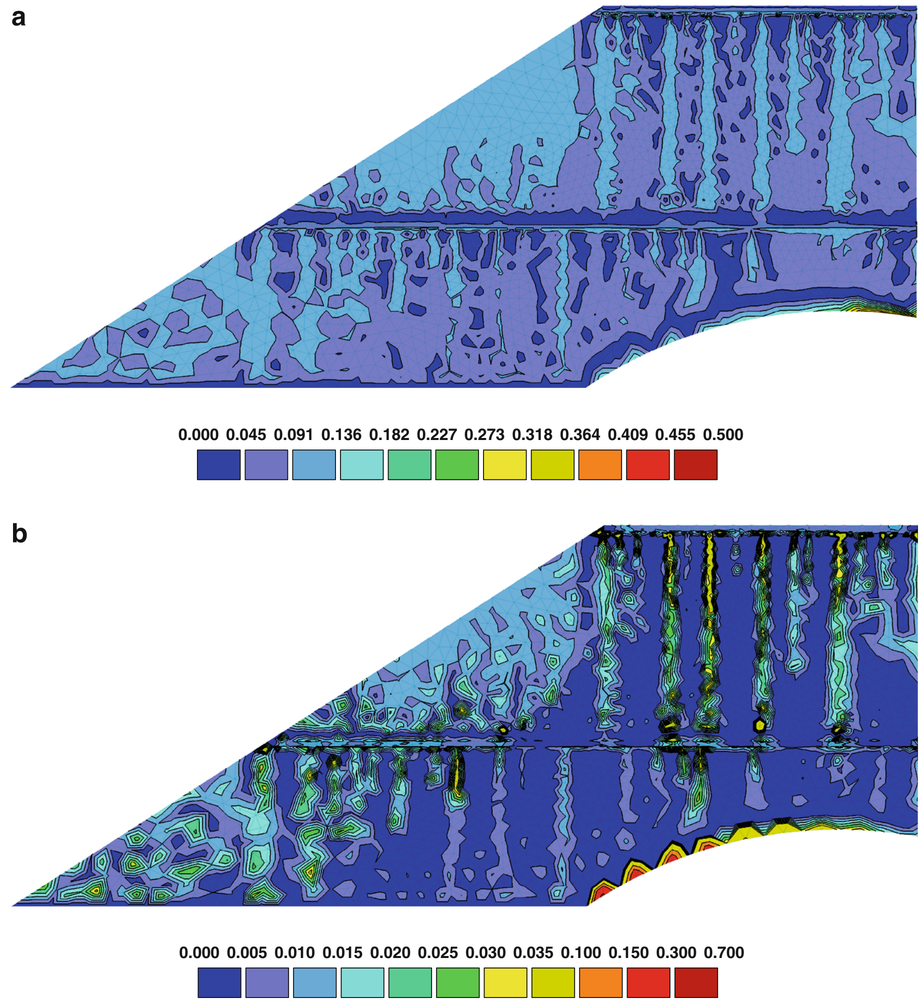

Fig. 9 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S10 (GRV with two *horizontal* SBL layers) at the end of December of the 10th year; small pile

retention capacity and the creation of a capillary barrier effect at the interface with the coarser waste rock. As water content increased in the fine-grained materials, the base of each compacted layer became more saturated. When the suction at an interface reaches the water entry value (WEV $\equiv \Psi_r$) on the water retention curve of the coarse GRV material, the capillary barrier effect tends to disappear (Aubertin et al. 2006, 2009); water can then infiltrate more deeply in localized flow zones (Fala et al. 2003, 2005). The wetting zones associated with such fingering infiltration develop gradually downward and laterally. The degree of saturation in these localized zones is higher (S_r is up to 40 %) than in adjacent areas in the gravelly waste rock (S_r less than 10 %), so that water velocity is much greater in the former than in the latter.

Simulations were also performed with inclined (sandy or silty) layers to assess the possibility of controlling infiltration in the core of a large waste rock pile. Results indicate that infiltrating water tends to follow the interfaces between the fine-grained material layers and the underlying coarse waste rock, as observed in previous studies (e.g. Aubertin et al. 2006, 2009; Bussière et al. 2003; Fala et al. 2003, 2005). Layers inclined at 5 and 10 % can help maintain a dryer center of the pile as the capillary barrier that develops between the fine- and coarse-grained materials causes the external portion of the pile to become more saturated than the central core. The magnitude of the effect of inclined layers depends on several factors including the hydrogeological properties of the adjacent materials, the thickness of the layers and their inclination angle, the amount of precipitation (recharge), the dimensions of the pile, and its shape. The geometry of the interfaces (flat vs. irregular) between the waste rock and compacted layers also influenced the motion of water inside the finer-grained material and the presence of localized water flow beneath the layers, as shown by our ongoing investigation on this aspect (not shown here).

Simulations were also conducted to assess the effect of the pile size on water movement, for a size reduced by a factor of 4 (height of 27 vs. 109 m). The results of this comparison showed that the wetting front arrived at the base of the smaller pile much faster than in the larger pile (as expected).

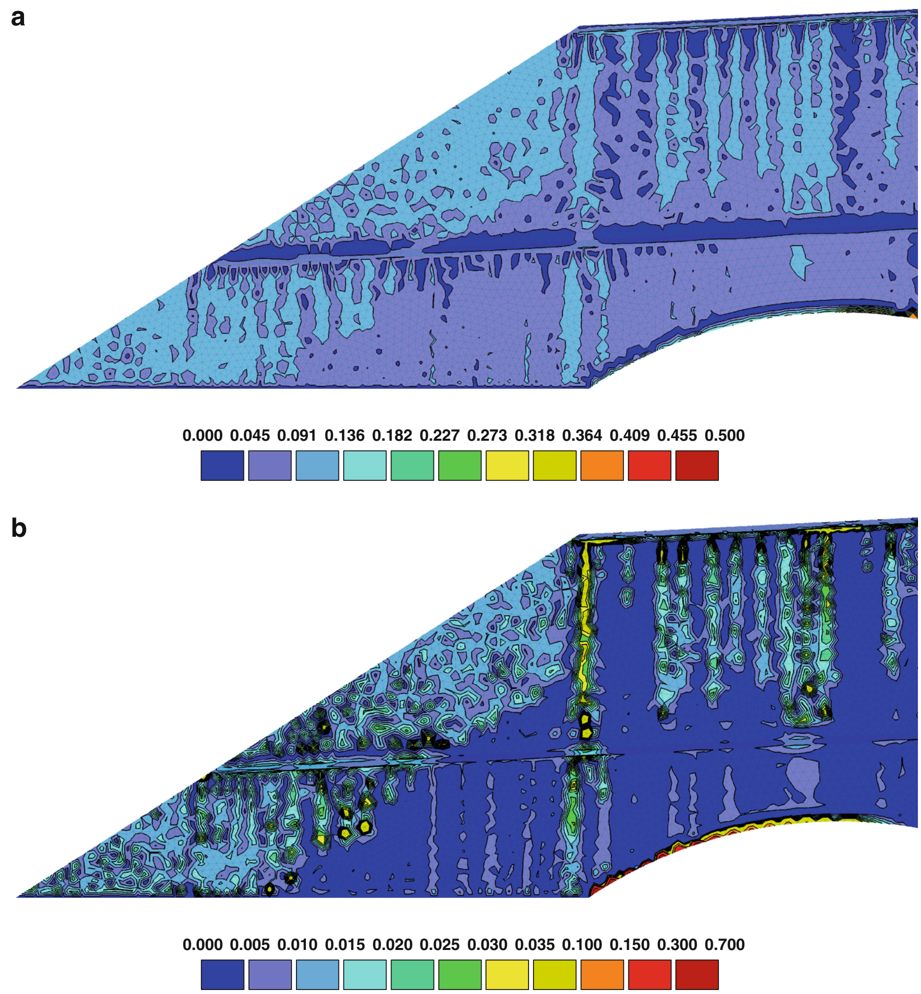

Fig. 10 Contours of **a** the volumetric water contents and **b** velocity, cm/h, for simulation S11 (GRV with two SBL layers inclined at 5 %) at the end of December of the 10th year; small pile

Taken together, these results provide valuable insights into the hydrogeological response of unsaturated waste rock piles. Nonetheless, the simulations presented here should be considered in the proper context, with their limitations. For instance, as was mentioned above, the calculations were conducted using Richards (1931) equation, which is based on Darcy's law. Various types of localised flow have been reported for waste rock, including the presence of turbulent flow. Such non-Darcian flow has been well documented for coarse-grained materials with large pores (Dexter 1993; Li et al. 1998), and has been observed during some experiments on waste rock (e.g. Andrina 2009; Eriksson et al. 1997; Nichol et al. 2005). This aspect was ignored in this investigation because the waste rock analysed here, which has been characterized in laboratory and field tests (e.g. Aubertin et al. 2005, 2008; Anterrieu et al. 2010; Dawood et al. 2011; Martin et al. 2005), showed no sign of turbulent flow. Water seepage in the core of such piles has been observed to essentially occur through waste rock with a sandy matrix. In this regard, the waste rock satisfies the typical grain size criterion that identifies conditions where Darcy's law applies (e.g. Morin et al. 1991; Smith and Beckie 2003). Nevertheless, it is recognized that localized turbulent flow can occur, particularly near the edge of piles (depending on the construction method used). For such cases, other numerical modeling avenues have been explored, including the use of dual-permeability media (Zhan 2000), adding layers with markedly different hydraulic characteristics in the model (Fala et al. 2005; Wilson et al. 2000), applying a stochastic distribution to define the hydrogeological properties (Fala 2008; Fala et al. 2012), and introducing localized flow channels in the form of planar discontinuities (fractures) in the medium (Broda et al. 2013).

Another limitation that should be kept in mind when analysing the simulations results on a fine scale is the influence of mesh size. The grids used here in the models were relatively coarse, mainly due to the computing time. For more detailed analyses (on a local scale) of unsaturated water flow and distribution, smaller mesh sizes, defined by criteria reviewed by Chapuis et al. (2001), should be used (see also Fala et al. 2005). However, on a broad scale, the mesh size used for the model construction did not affect the accuracy of the numerical solution, which was evaluated by comparing the input and output hydraulic functions and by computing the relative error in the water mass balance. It should be noted that HYDRUS-2D does not relate the absolute error to the volume of water in the flow domain, but instead expresses this error in terms of the maximum value of two quantities: the sum of the absolute changes in water content over the complete grid (all elements) and the sum of the absolute value of all fluxes in and out the flow domain (Šimunek et al. 1999). The relative errors in the water mass balance at each registered time for simulations S1 to S11 (Supplemental Table 4) are typically much smaller than 1 %, indicating that the accuracy of the numerical solutions was quite acceptable.

The results presented here provide some indication and guidance for designing waste rock piles in which water flow needs to be controlled. Such control may be needed to prevent the release of contaminants from reactive minerals.

The results also illustrate the importance of carefully planning the design of waste rock piles. Various proposals have been put forward to improve the configurations and methods of construction of piles, by including areas promoting controlled drainage and reducing infiltration and water accumulation in their core (Aubertin 2013; Aubertin et al. 2002b; Fala 2008; Fala et al. 2003, 2005, 2006; Molson et al. 2005; Wels et al. 2003; Williams et al. 2008). But such methods are not yet commonly used in practice and the construction of waste rock piles is still largely dictated by operational and financial considerations, which are mainly based on short-term analysis. In the longer term, however, it is advantageous to plan the construction of piles to minimize geotechnical and hydro-geochemical problems during and after mining. The modeling tools presented above can also be used to study and compare various scenarios to arrive at an optimal design.

Conclusion

The simulations presented in this paper indicate that horizontal layers can negatively affect water movement inside a large waste rock pile by favoring flow deep into the core of the pile. The effects of the layers may be less critical when these are inclined outward or when they are made of a finer-grained material, as water then tends to follow the inclination of the layers, hence protecting (in part) the core of the pile from extensive wetting. The actual effect of the layers depend on a number of factors, including the size of the pile, the precipitation (recharge) regime, the number of layers, their inclination, and material properties.

Identifying areas where capillary barrier effects can develop is an essential element for the design and construction of a waste rock pile because these effects tend to favour the accumulation of water and the appearance of localized flow. These phenomena can occur naturally as a result of the construction method, but can also be produced intentionally during construction by controlling the position, configuration, and properties of the compacted layers. The dense material layers (that cause capillary barrier effects) can help divert water outside the pile and thus improve the quality of the percolating waters. The effects of other parameters and factors, including non-homogeneous material properties of the waste rock (e.g. Broda et al. 2013; Fala et al. 2012) also need to be investigated further.

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