A numerical investigation of the influence of internal structure on the unsaturated flow in a large waste rock pile

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ABSTRACT
The mechanical operations used for waste rock pile construction affect its internal structure. In this study, long term numerical simulations of unsaturated flow in a large waste rock pile are conducted to investigate the effect of structural features. The simulations lead to various observations that provide a better understanding of the long term hydrological behaviour of waste rock piles. The results obtained show that water flux at the base of a pile can be significantly affected by the presence of fine grained material layers in the pile. The paper presents the main results of the calculations, with some comments on their practical implications for pile design.

RÉSUMÉ
Les opérations mécaniques utilisées pour la construction d'une halde à stériles affectent sa structure interne. Dans cette étude, des simulations numériques à long terme sont menées afin d'analyser l'écoulement non saturé dans une grande halde à stériles, en variant ses caractéristiques structuralles. Les simulations conduisent à diverses observations qui mènent à une meilleure compréhension du comportement hydrogéologique de la halde. Les résultats obtenus montrent notamment que les flux d'eau à la base d'une halde peuvent être considérablement affectés par la présence de couches de matériaux fins dans celle-ci. L'article présente les principaux résultats de ces calculs, avec quelques commentaires sur leur implication pour la conception des haldes.

1 INTRODUCTION

Waste rock is a by-product of mining activities that can be produced in large volume, depending on the mining method. Such waste rock is typically placed in a pile on the mine site surface. The heavy equipment used for pile construction affects its internal structure. Typical construction methods often lead to the creation of layers of compacted material in the pile that affect its hydrogeological behaviour (e.g. Aubertin et al. 2002, 2005, 2008; Fala, 2002; Martin 2003; Martin et al. 2005). The fact that waste rocks show a widely graded size distribution further increases the complexity of piles.

The environmental response of a pile also depends on the mineralogical composition of the waste rock. Acid mine drainage (AMD) or contaminated neutral drainage (CND) can be produced if the waste rock contains reactive minerals (e.g. Lefebvre et al. 2001; Ritchie 2003; Sracek et al. 2004, 2006, Stantec 2004; Bussière et al. 2005). Such seepage waters may have harmful impacts on the surrounding environment, and thus need efficient control measures to prevent or eliminate these undesirable effects. The best control approach begins with a design that limits water infiltration and flow within the pile (Aubertin et al. 2002, 2005, 2008; Fala et al. 2003, 2005, 2006; Wels et al. 2003; Williams and Rohde 2007). However, analysing the hydrogeological behaviour of a waste rock pile is not a simple task. In this regard, numerical simulations are quite useful to obtain a better understanding of the factors that affect the response of a pile. The finite element code HYDRUS-2D (version 2.0; Simunek et al., 1999) has been used in this study to conduct a series of unsaturated water flow simulations inside a large waste rock pile, using Richards (1930) equation. The main details of the calculations are presented in the following, with some key results.

2 MODEL CHARACTERISTICS

A parametric study has been conducted to assess the potential effects of internal features on the long term hydrological response of a large waste rock pile. This article focuses mainly on the effect of fine grained material layers inside the pile, including their number, inclination, and material properties. The waste rock pile model has a width of 260 m (with an impervious vertical boundary) and a height of 109 m (Fig. 1). It is opened to the atmospheric conditions. The base of the pile consists of two parts: the first area (on the right hand side of Fig.1) is made of an impervious rock, and the second area represents the water table (i.e. the rest of the pile is under water). The impervious boundary condition imposed on the right hand side of the pile represents a vertical line of separation for the flow net inside the pile. The residual water content is used to establish the initial condition for each simulation. Three types of materials are used in this study to represent the different fractions of the waste rock inside the pile: a gravel, a sand, and a silt. The materials properties are based on laboratory and field tests conducted on waste rocks in recent years (Aubertin et al. 2005, 2008). The hydraulic parameters for these materials are given in Table 1, based on the van Genuchten (1980) model, which is commonly used to define the water retention curve and the unsaturated hydraulic function; these can be expressed as follows:

$$K(h) = K_s S_e^{1/2}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \qquad [1]$$

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha_v h)^n\right]^m} \quad [2]$$

Where $S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$ and $m = 1 - \frac{1}{n}$ $\quad n > 1$

In these equations, K is the hydraulic conductivity, K_s is the saturated hydraulic conductivity, h is the pressure head, S_e is an effective degree of saturation, θ is the volumetric water content, θ_r is the residual water content, θ_s is the saturated water content, α_v and n are van Genuchten model parameters.

The climatic conditions (precipitation – evaporation cycles) used in this study are based on the monthly average values measured at the Latulipe, Quebec (Canada) monitoring station (as provided in Fala et al. 2003, 2006); the monthly distribution is given in Table 2. Different scenarios are simulated to assess the effects of various factors; these are summarized in Table 3.

Table 1. The van Genuchten (1980) model parameters for the materials used in the numerical study.

Material	θ_r	θ_s	α_v (cm^{-1})	n_v	K_s (cm/s)
Gravel	0	0.39	149.6	1.45	0.47
Sand	0.01	0.29	0.03	3.72	0.0051
Silt	0.034	0.46	0.016	1.37	6.94×10^{-5}

Table 2. Climatic conditions used in the modeling (in cm/day)

	Precipitation	Evaporation
January	0.182	0 (frozen surface)
February	0.15	0 (frozen surface)
March	0.191	0 (frozen surface)
April	0.22	0.046
May	0.258	0.237
June	0.307	0.339
July	0.302	0.407
August	0.314	0.345
September	0.324	0.21
October	0.293	0.089
November	0.231	0 (frozen surface)
December	0.23	0 (frozen surface)

Table 3. Simulated scenarios

Simulation	Main material	Fine grained material	No. of fine material layers	Layers inclination
S2	Gravel	Sand	1	Horizontal
S3	Gravel	Sand	2	Horizontal
S4	Gravel	Sand	3	Horizontal
S5	Gravel	Sand	4	Horizontal
S6	Gravel	Sand	2	5%
S7	Gravel	Sand	3	5%
S8	Gravel	Sand	2	10%
S9	Gravel	Silt	2	Horizontal
S10	Gravel	Silt	2	5%
S11	Gravel	Silt	2	10%

3 MAIN RESULTS

3.1 Base Case

The gravely material properties have been used to simulate the base case (homogeneous pile) for a period of 10 years. Figure 2 shows the final results for the volumetric water content (along line AA – see Fig. 1) and water velocity distributions (along lines AA, BB, and CC). It is seen that the values of volumetric water content is under 0.1 and that water velocities are typically less than 0.014 cm/hr. Also, the water velocity at the base of the pile (CC line) tends to decrease from left to right, and it reaches approximately zero at x =110 m.

3.2 Effect of Horizontal Layers

A layer of sandy material, 50 cm thick, was added on top of the pile to represent the effect of surface compaction by the machinery. The program was run with the same initial and boundary conditions shown in Figure 1 and given in Tables 1 and 2. Figure 3 shows the results with the effects of the adding of the sand layer after 10 years (simulation S2). It is seen that the volumetric water content increases in the sand layer, which tends to create a capillary barrier on the top of the pile. However, there is little effect of this added sand layer on water transport inside the pile itself. The sand layer causes an accumulation of water, which escapes downward, causing the appearance of more localised flow zones in the pile.

Two sand layers were included in the next simulation (S3): one on top and one on the middle of the pile (to represent the effect of a previously compacted surface). The results of the simulation after 10 years are shown in Figure 4. The vertical profile of the volumetric water content (along line AA) shows the capillary barrier effect created by the different hydraulic properties for the sand layers and gravel material. This causes the volumetric water content in the sand layers to be larger than in the rest of the pile. Water velocities are increased to 0.03 cm/hr in the sand layers, while they are less than 0.02 cm/hr in the coarse waste rock. This increase in velocity is attributed to the increased localized flow.

Two additional simulations were conducted with three and four sand layers added at regular intervals in the pile (S4 and S5). The results show that there is little difference in the water content distribution between results obtained with two and three layers (Fig. 5). On the other hand, the water velocity appears to be significantly reduced (≤ 0.01 cm/hr) in the pile, while it is somewhat higher (around 0.03 cm/hr) in the 3 sand layers. The calculation results also show that there is no significant difference between the results obtained with three (S4) and four (S5, not presented here) layers.

3.3 Layers Inclination

Previous simulation results, obtained on a smaller pile, have shown that sandy layers can help in reducing water flow deep inside the pile when the layers are inclined outward (Fala et al. 2003, 2005, 2006). Figure 6 shows the simulation results after 10 years for the large size pile with two sand layers (50 cm thick) inclined at 5%. It shows that water content and velocity along line AA have been decreased when compared with the results shown in Figure 4. This reduction is due to the direction of water flow, which is affected by the inclination of the sandy layers. Fairly similar results are also obtained when three inclined sand layers are used (S7, not shown here).

Despite the visible effect, the sand layers inclined at 5% do not appear to be as effective to control the flow inside the large pile (compared to the smaller pile analysed previously).

In simulation S8, the two sand layers have been inclined at 10%; the results are shown in Figure 7. These indicate that water velocity has been significantly reduced with the two sandy layers. Hence, a larger inclination may be required to obtain a significant effect in the case of a larger waste rock pile.

3.4 Material properties

The results presented above indicate that sand layers have a limited effect on water flow in the large pile (except when the layers are inclined at 10%). The next step taken here was to replace the sandy material with a finer grained material, to increase the difference of hydraulic properties between the waste rock and the internal layers. The silty material layers used here have the hydraulic properties shown in Table 1. Figure 8 shows the simulation results (S9) when two horizontal silt layers are used. As can be seen, there is no major difference between the results obtained with two horizontal sand layers (Figure 4) and with two horizontal silt layers. In the next simulations, the two silt layers have then be inclined at 5% and 10 %; the results are shown in Figure 9 and 10, respectively. Figure 9 shows that there is no significant effect of having two silt layers inclined at 5%. However, there is again a significant difference in the results when the two layers are inclined by 10 % (Figure 10).

4. FINAL COMMENTS

The results presented above indicate that the presence of fine material layers can, in some cases, reduce the velocity and flow of water inside a large waste rock pile. The actual effect of the layers depend on a number of factors, including the height of the pile, the precipitation regime, the number of layers, their inclination, and the material properties. The effects of other parameters are under investigation, and the results will be presented elsewhere.

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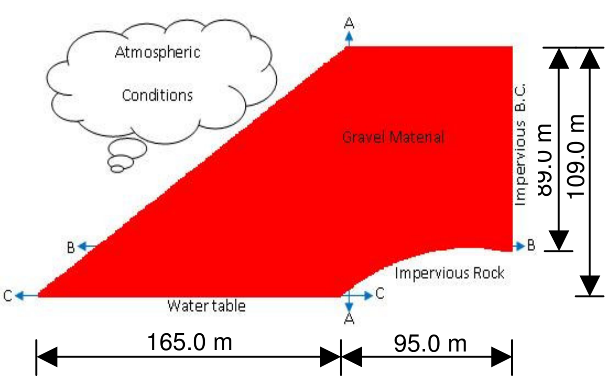

Figure 1. The geometry and boundary conditions for the waste rock pile simulations. The profiles positions are: line AA (on x = 165m from the left), line BB and line CC (at Y = 89m and 109 m from the top of pile, respectively)

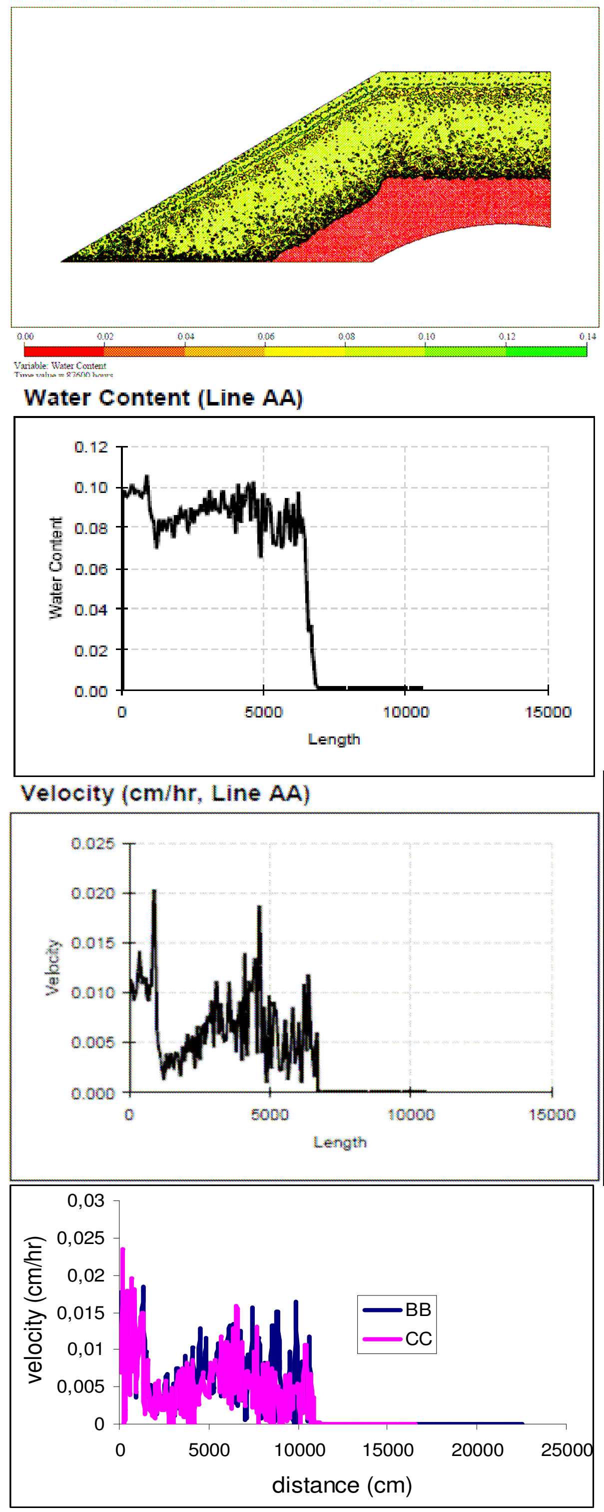

Figure 2. Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom).

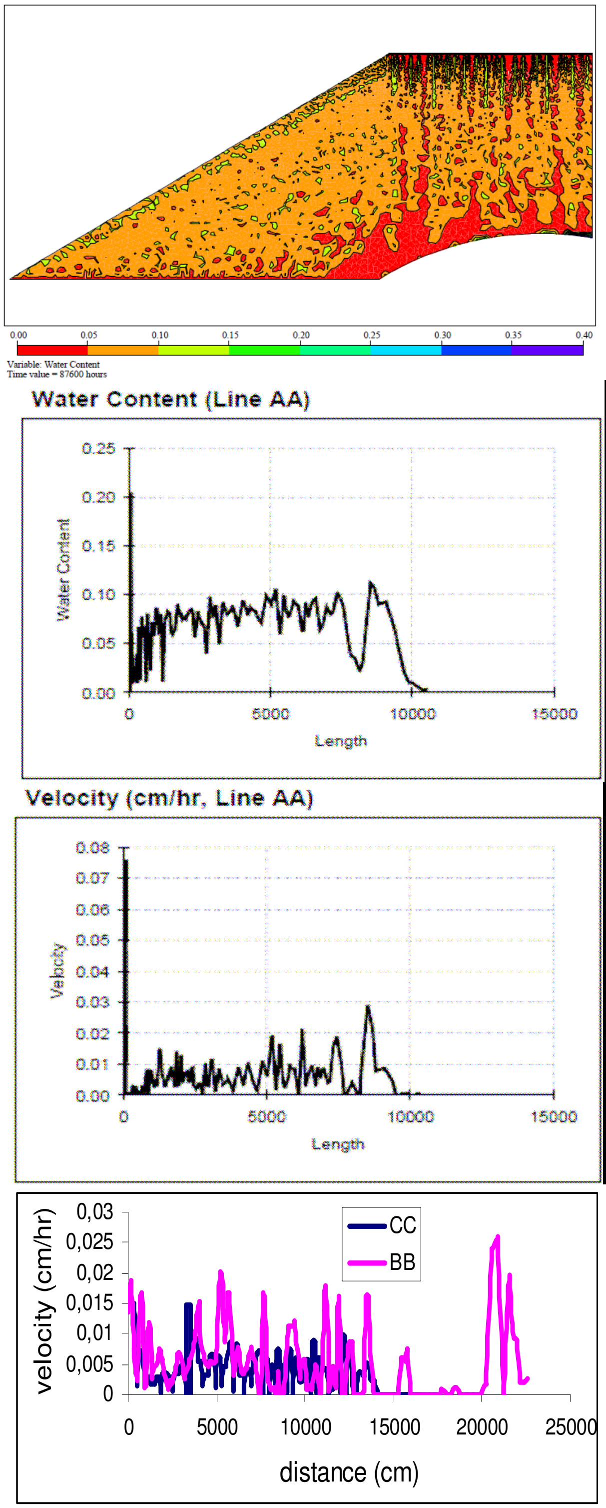

Figure 3. Simulation S2: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). One sand layer is added on top of the pile.

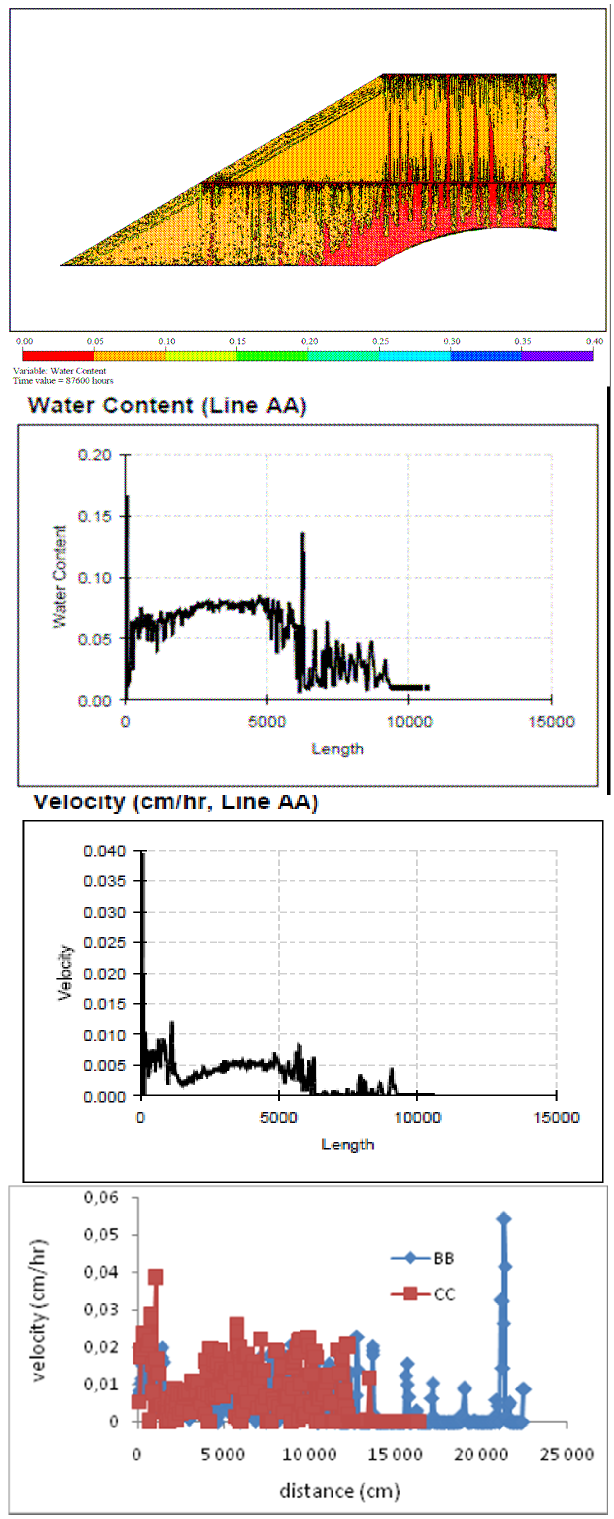

Figure 4. Simulation S3: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). Two sand layers are added on top and at the center (mid-height) of the pile.

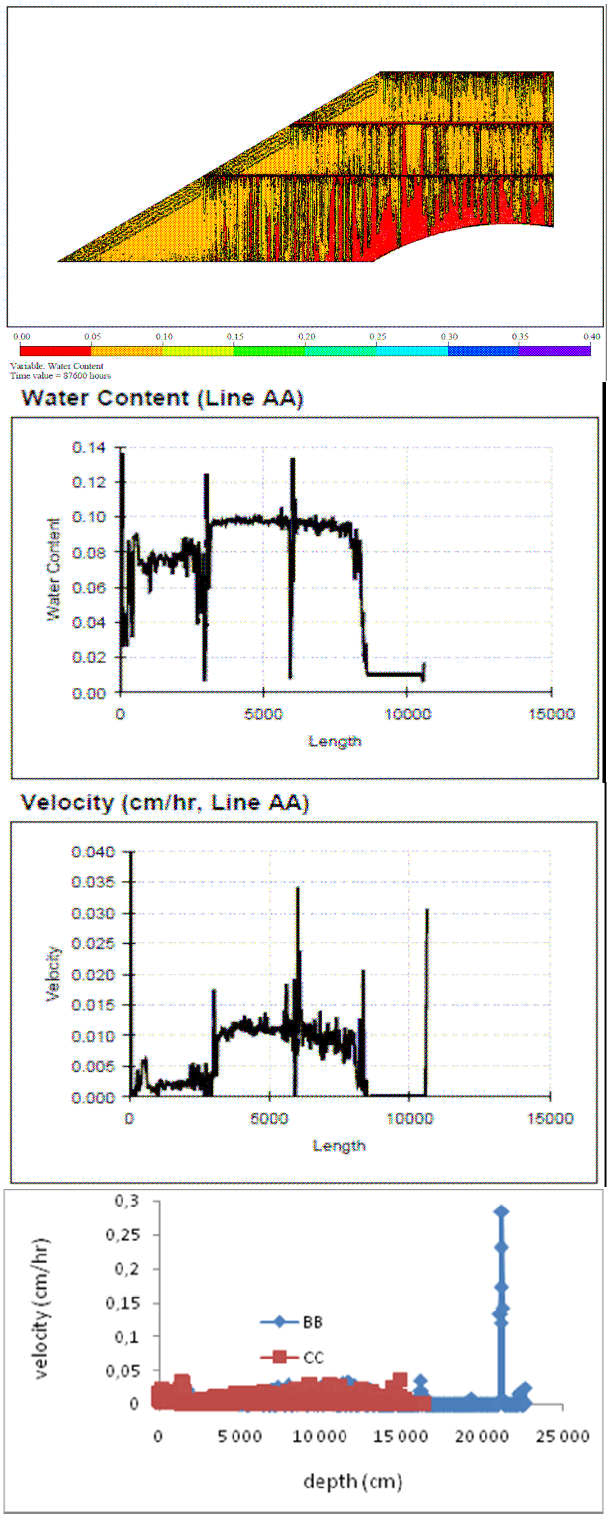

Figure 5. Simulation S4: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). Three sand layers are added at regular intervals inside the pile.

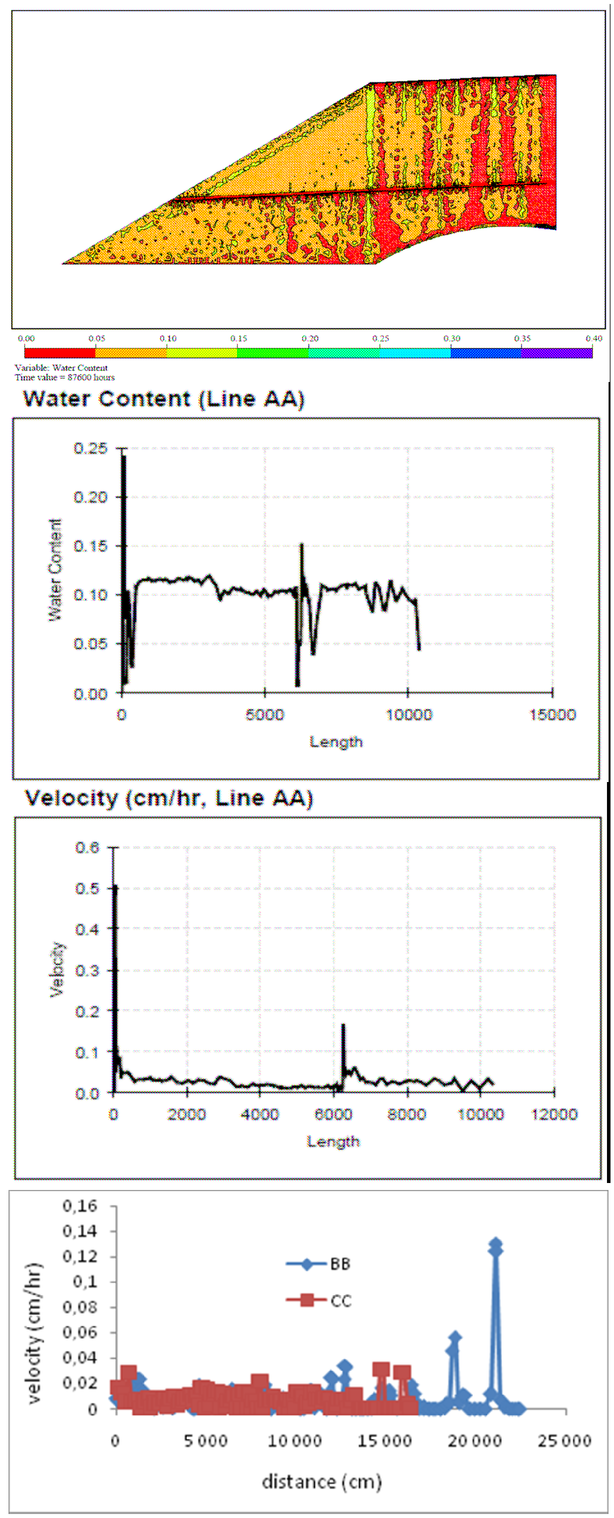

Figure 6. Simulation S6: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). The two sand layers added on top and at mid-height of the pile are inclined at 5%.

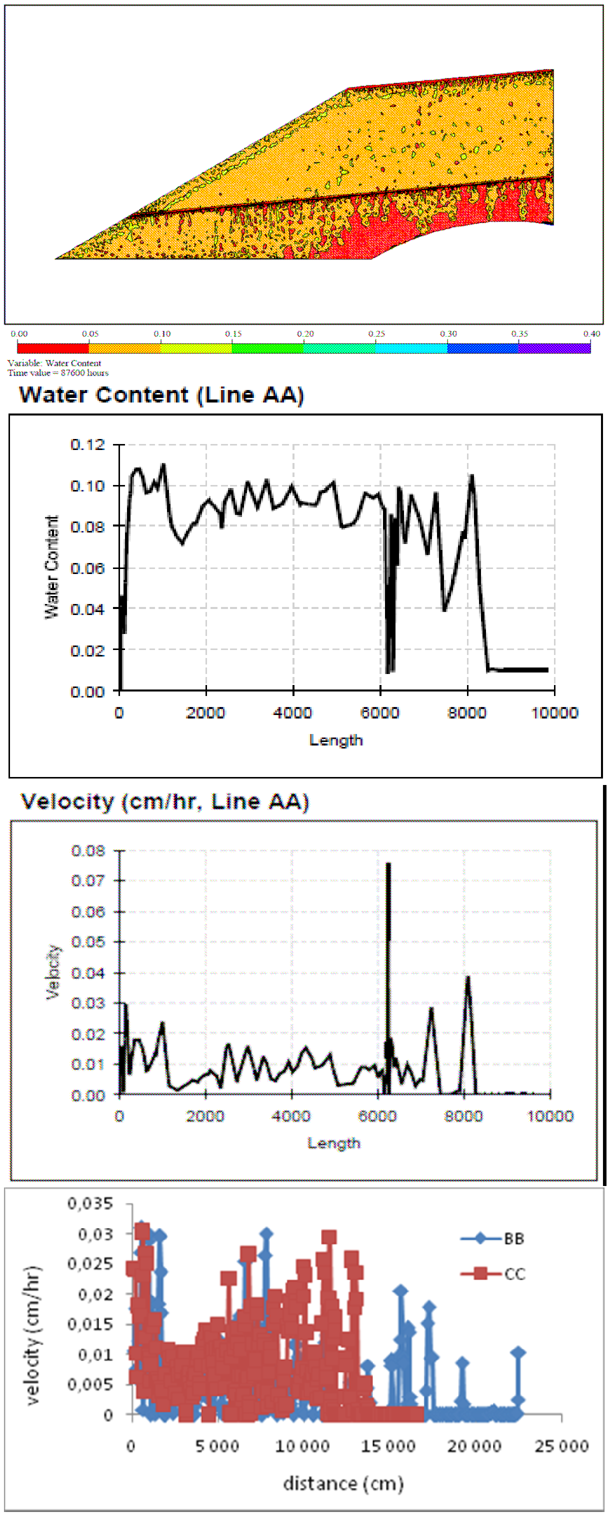

Figure 7. Simulation S8: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). The two sand layers added on top and at mid-height of the pile are inclined at 10%.

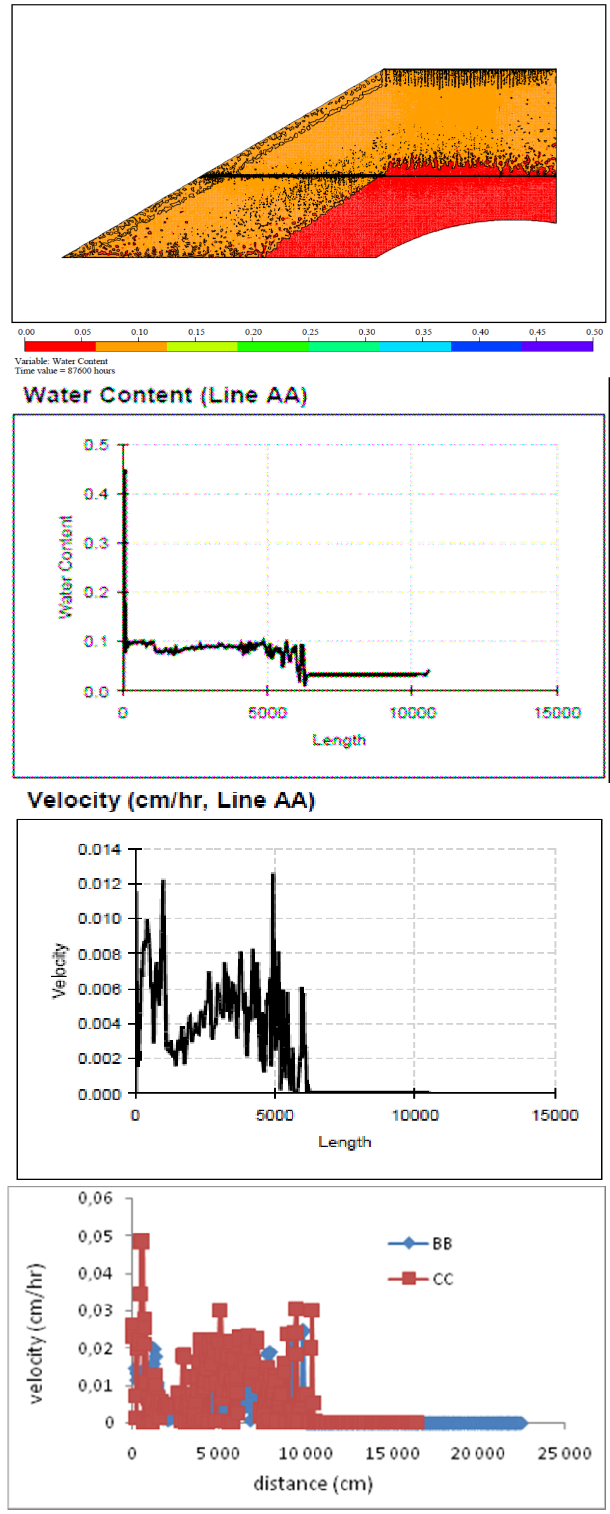

Figure 8. Simulation S9: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). Two horizontal silt layers are added on top and at mid-height of the pile.

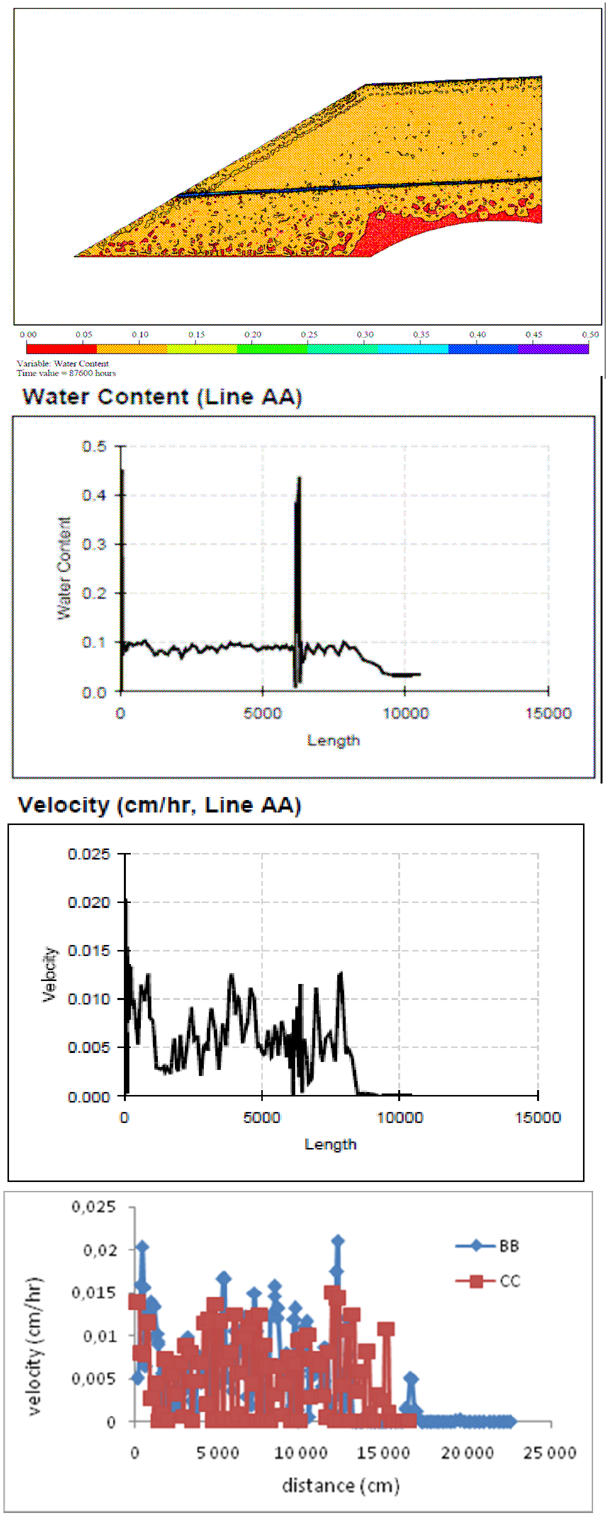

Figure 9. Simulation S10: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). The two silt layers added on top and at mid-height of the pile are inclined at 5%.

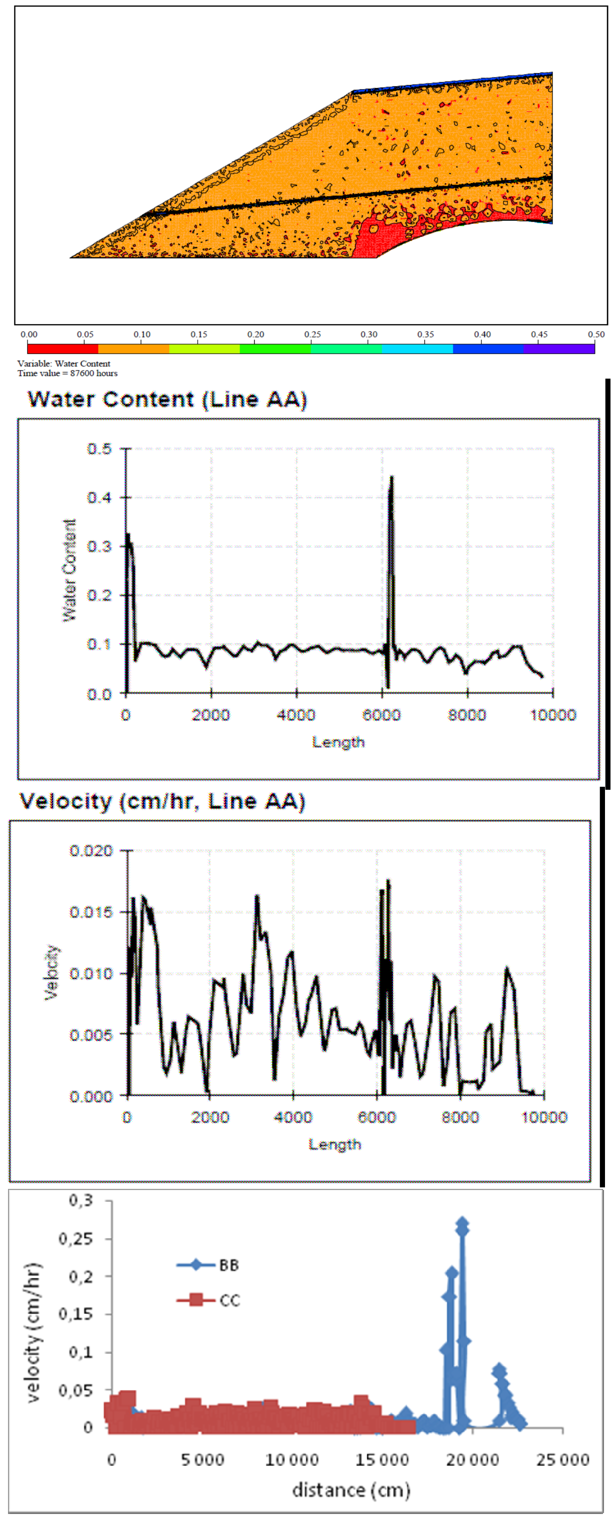

Figure 10. Simulation S11: Contour distribution of the volumetric water content (top); vertical profile of the volumetric water content and water velocity along line AA (center); vertical water velocity along lines BB and CC (bottom). The two silt layers added on top and at mid-height of the pile and inclined at 10%.