EVALUATION OF UNSATURATED FLOW IN MINE WASTE ROCK

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ABSTRACT
This project consists in studying some key hydrogeological properties of mine waste rocks and to evaluate the factors that influence flow of water in these materials. The aim is to improve characterization methods in the field and in the lab and to develop more representative models. The field work helped better understand the effect of surface layers compacted by heavy machinery on the pile hydrogeology. Laboratory tests showed that the coarse grain fraction (diameter greater than 5 mm) can play a significant role in the value of the saturated hydraulic conductivity and the water retention curve. Numerical calculations were performed to investigate the unsaturated flow conditions in the pile, for various configurations and properties. The numerical models, which were based on a typical geometry for waste rock dumps, showed that the water entry value of the materials can play an important role in the amount of infiltration into the pile.

RÉSUMÉ
Ce projet visait à étudier les propriétés hydrogéologiques des stériles miniers et à évaluer les facteurs qui influencent l'écoulement de l'eau dans les empilements de stériles. On veut ainsi améliorer la caractérisation de ces matériaux sur le terrain et dans le laboratoire pour obtenir des résultats de modélisation numérique plus représentatifs. Les travaux sur le terrain ont permis de mieux comprendre l'effet des couches compactées par la machinerie lourde sur l'hydrogéologie des haldes à stériles. Les essais de laboratoire ont montré que la partie plus grossière (diamètre des grains supérieur à 5 mm) joue un rôle important sur la valeur de la conductivité hydraulique saturée et de la courbe de rétention d'eau. Les modèles numériques, qui sont basés sur des géométries réels de haldes à stériles, ont mis en lumière l'importance de la pression d'entrée d'eau sur la quantité d'infiltration dans les empilements de stériles.

1. INTRODUCTION

To access the orebody, in a mining operation, it is generally necessary to extract waste rock. These rocks are usually stored on surface in piles, or in previously excavated stopes. The surface waste piles can be very large, with a height greater than 100 meters and an area of many tens of hectares. In some cases, the waste rock contains sulphur rich minerals that can react with water and oxygen and generate acid mine drainage (AMD). Waste rock piles usually have properties that favor the flow of fluids (water and air) and consequently, the development of AMD, such as high material heterogeneity, segregation in the pile caused by the waste rock dumping method, presence of preferential flow paths and low saturation level of the material in the pile (e.g. Aubertin *et al.* 2002a, 2002b). To minimize AMD production, it is therefore important to have a good grasp of the components influencing flow of water in the waste rock piles.

This project consisted in studying the flow of water inside waste rock piles. It was divided into three parts: field work on a mine site, characterization of samples collected on the waste rock dumps, and numerical modeling of sample cases to better understand unsaturated flow inside the dumps.

2. FIELD WORK

The field work for this project was completed in October 2001 on the waste rock dumps of the Goldstrike mine. This mine, which is a property of Barrick Gold, is located on the Carlin Trend in northern Nevada. The objective of this work was to gain a better understanding of the mechanisms affecting unsaturated flow in the waste rock dumps and also to collect samples for future laboratory characterization. The field work discussed in this paper includes infiltration tests completed on the surface of the waste rock dump and density measurements on various areas of the dump.

2.1 Infiltration tests

An air-entry permeameter was used to measure the infiltration capacity of the studied waste rock pile. Two tests results are considered here. The first one (TP-1) was conducted at the crest of a bench while the other test (TP-2) was done on a highly compacted area. The procedure used for this test is based on ASTM D 5126-90 standard.

Using the results from the tests, the field saturated hydraulic conductivity can be estimated using equation 1, below:

$$k_{fs} = \frac{L_f (\partial H_r/\partial t)(r_r/r_c)^2}{H_r + L_f - (P/(2\rho g))} \qquad [1]$$

where : k_{fs} = field saturated hydraulic conductivity (m/s).

L_f = depth of the wetting front (m).

$\partial H_r / \partial t$ = rate of fall just before water supply was shut off (m/s).

H_r = ponded height of water above the soil (m).

r_r = reservoir radius (m).

r_c = injection cylinder radius (m).

$P/(2\rho g)$ = air entry value which is equal to the minimum pressure divided by the unit weight of liquid (m).

Using equation 1, it was estimated that the field saturated hydraulic conductivity is about 7.7 x 10^{-8} m/s at the TP-1 location, and 5.1 x 10^{-9} m/s at TP-2. These fairly low values are related to the relatively fine gradation of the waste rock on the pile and may also reflect the influence of the compacted layer on the surface of the waste rock dump (as an air-entry permeameter essentially measures the hydraulic conductivity to a depth of approximately 10 cm).

2.2 Density Measurements

At the surface of the bench of a waste rock dump the material is often compacted by the circulation of heavy machinery. To evaluate the properties of this zone, thirteen measurements were taken using a nuclear density probe on the surface of the waste rock dump of the Goldstrike mine site. Table 1 gives a summary of the properties of interest that can be obtained from these tests. No density measurements were taken in the Carlin silt.

Table 1. Average results obtained with the nuclear density probe on the surface of the waste rock pile.

Characteristics	Value	Std. dev.
Density - γ (kN/m^3)	20.4	0.3
Dry density - γ_d (kN/m^3)	19.6	0.3
Porosity - n	0.26	1.10x10^{-2}
Degree of saturation - S_r	29.30%	14.76%
Volumetric water content - θ	0.08	4.05x10^{-2}

As can be noticed in Table 1, most of the values are in the same range, with very small standard deviations between the results. The only exception is the degree of saturation whose standard deviation is almost half of the average value. There are many reasons that may explain this, such as heterogeneity in gradation, intensity of surface evaporation and frequency of circulation of the water truck. However, this result does not influence the fundamental results, which are that, although many measurements were taken at different locations on a very large waste rock dump, the values are always in the same range.

As mentioned above, the presence of a compacted zone at the surface of the benches of a waste rock dump could influence the water infiltration properties. The results of density measurements taken at different depths in a 2.0-meter deep trench are shown in Figure 1 below.

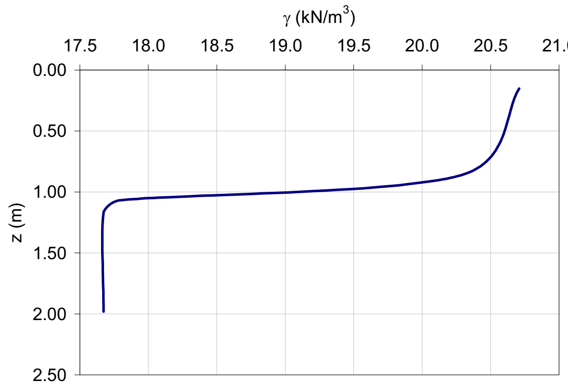

Figure 1. Evolution of the density (γ) with respect to depth from surface.

Figure 1 indicates there is a zone of higher density at the surface of the waste rock dump. The thickness of this denser zone is approximately 1.0 meter. In this case, the transition between the compacted and the uncompacted areas is fairly sharp. The presence of the compacted zone, containing materials of different properties, influences the hydrogeological properties of the waste rock dump. Because of the higher density and finer materials in these zones, the compacted layers have a greater ability to retain water than the waste rock found below.

The particles composing the waste rock pile might degrade as densification occurs. This increases the amount of finer particles in the pile and modifies the hydraulic properties of the system.

3. LABORATORY CHARACTERIZATION

During the field campaign, samples were collected and divided into three sample types:

- Waste rock 1 (WR-1);
- Waste rock 2 (WR-2);
- Inert overburden (Carlin silt).

The samples used for the laboratory characterization were not collected in a compacted zone.

Using these samples, laboratory tests were performed to obtain some of the main materials properties. This section presents and discusses the results that were obtained; more information on these tests can be found in Martin (2003).

3.1 Basic properties

The tests completed on the geotechnical properties of the samples presented in this paper include the grain size curves and the solid grain density.

The grain size tests were done according to standard D 422 of the ASTM. To facilitate transportation of the samples from the site to the laboratory, most of the material with a diameter greater than 25 mm was removed in the field. The grain size curves are separated into three categories: the full sample as received in the laboratory, the curve up to a maximum grain size of 20 mm and the curve up to a maximum grain size of 5 mm. Figure 2 shows the grain size curves of the samples collected on the site.

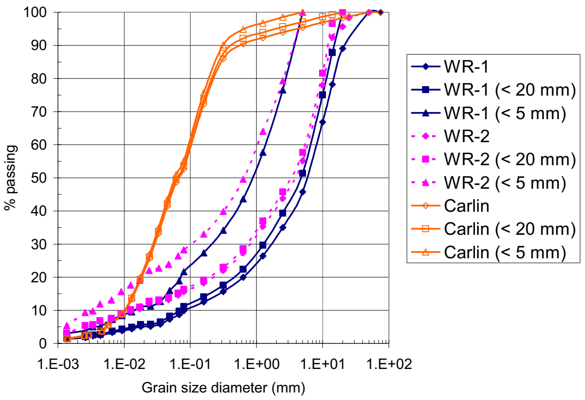

Figure 2. Grain size curves of the materials collected on the Goldstrike site.

Figure 2 shows that the waste rock samples are well graded gravels or sands, depending on the cutoff size of the material. According to the USCS classification system, the waste rock samples are classified as silty gravel with sand (GM). As for the Carlin material, it is classified as sandy silt (ML) since it has no plastic limit and a very low liquid limit.

Following the grain size analysis, the specific gravity (G_s) of the three materials was obtained using ASTM standard C 127. Table 2 summarizes the results.

Table 2. Specific gravity (G_s) of the samples collected on the Goldstrike site.

Material	G_s (-)
WR-1	2,62
WR-2	2,68
Carlin	2,48

The analysis of the basic properties of the waste rock and overburden from the Goldstrike site shows that, although waste rock is composed of coarse particles, there is also a relatively important amount of finer (silt sized) particles which could possibly influence the other properties of the material.

3.2 Hydrogeological properties

Hydrogeological properties of the waste rock and overburden (Carlin) materials collected on the site were evaluated in the laboratory. The properties of interest are the saturated hydraulic conductivity and the water retention curve WRC (or soil-water characteristic curve SWCC).

The saturated hydraulic conductivity (k) was obtained by two different types of tests: flexible wall permeameter using a maximum particle size of 5 mm and large size rigid wall permeameter using a maximum particle size of 20 mm. Because it is a finer material, the larger permeameters were not used with the Carlin. Table 3 shows the average results obtained for the three materials sampled at the Goldstrike mine.

Table 3. Average results of the laboratory permeability tests conducted on the samples from the Goldstrike mine.

Material	k (m/s) Flexible wall (fine fraction)	k (m/s) Large size rigid wall
WR-1	6.0×10^{-9}	3.7×10^{-5}
WR-2	2.3×10^{-7}	6.1×10^{-5}
Carlin	1.3×10^{-6}	N/A

These results indicate that the saturated hydraulic conductivity (k) is affected by the amount of coarse material in the waste rock. The difference in the values between the small permeameters and large size rigid wall permeameters is up to four orders of magnitude for the WR-1 and two orders of magnitude for the WR-2. The results obtained with the flexible wall permeameters for the waste rock samples compare to the values obtained with the air entry permeameter where the field saturated hydraulic conductivity (k_{fs}) was around 10^{-8} m/s. The saturated hydraulic conductivity of the Carlin material is comparable to that of a sandy silt (ML) with an average value of 1.3×10^{-6} m/s.

Waste rocks in dumps are usually unsaturated so it is important to obtain the water retention curve (WRC) of the materials that compose the pile. Since the apparatus available in the laboratory (Tempe cell) did not allow the use of particles coarser than 5 mm, it was decided to obtain the WRC of the waste rock using the Modified Kovàcs (MK) predictive model which has been used successfully to estimate the WRC of similar materials, when compared to column tests results (Gamache-Rochette 2004). A description of this model is beyond the scope of this paper and its validation has been done in other publications (Aubertin *et al.* 2003). The properties required to obtain the WRC using this model are the grain size curve of the material (D_{10} and D_{60}) and the void ratio (e). The input values used for the WR-1 and WR-2 are given in Table 4 below.

Table 4. Materials properties of the WR-1 and WR-2 used as input values in the MK model.

Material	D_{10} (mm)	D_{60} (mm)	e (-)
WR-1	0.067	6.68	0.67
WR-2	0.012	5.50	0.67

In Table 4, the void ratio (e) is the maximum value observed in the field from the nuclear density probe measurements. Using the values in Table 4 and the MK model, estimates of the water retention curves were obtained (Figure 3). The WRC of the Carlin material was obtained from tests in Tempe cells. The laboratory results were then smoothed and averaged with the software RETC (van Genuchten *et al.* 1991).

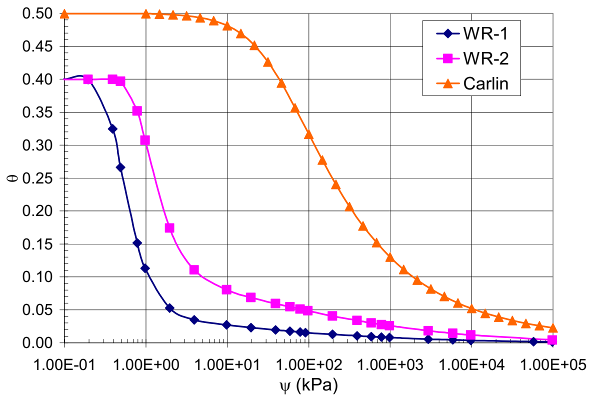

Figure 3. Water retention curves of the waste rock materials (WR-1 and WR-2) (predicted with the MK model) and of the Carlin material (fitted with van Genuchten (1980) model).

The air entry value (ψ_a or AEV) of the materials on Figure 3, is about 0.2 kPa for the WR-1 and 0.5 kPa for the WR-2 (based on the full grain size of the samples). The water entry value (ψ_w or WEV) is estimated at 2 kPa and 3 kPa for the WR-1 and WR-2 respectively. These values are comparable to what is given in the literature for waste rock materials (e.g. Herasymuik 1996). The AEV and WEV of the Carlin are about 10 kPa and 1,000 kPa respectively.

The unsaturated hydraulic conductivity (k_u) of the materials was then predicted using a simplified version (a closed-form analytical formula) of the Mualem (1976) predictive model proposed by van Genuchten (1980). Figure 4 shows these curves for the WR-1, the WR-2 and the Carlin silt based on the WRC shown on Figure 3.

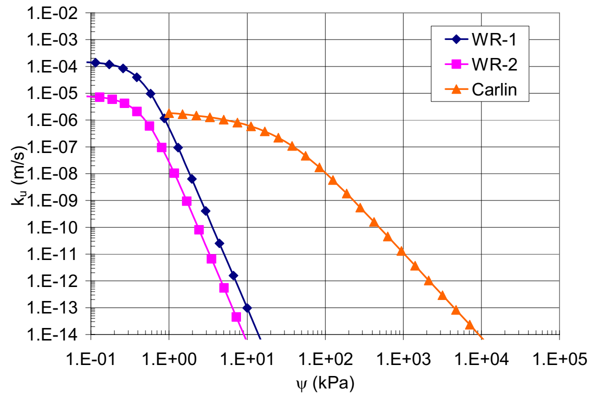

Figure 4. Unsaturated hydraulic conductivity curves (K_u) of the waste rock materials (WR-1 and WR-2) and of the Carlin collected on the Goldstrike property predicted using the Mualem (1976) – van Genuchten (1980) model.

The values of the saturated hydraulic conductivity of WR-1 and WR-2 were predicted using the Modified Kozeny-Carman (KCM) model (Mbonimpa *et al.* 2002), their values are 1.5 x 10^{-4} m/s for the WR-1 and 8.2 x 10^{-6} m/s for the WR-2. The predicted saturated hydraulic conductivities calculated with this model are about one order of magnitude larger for the WR-1 and one order of magnitude smaller for the WR-2 than the values measured with the permeameters on the material with a maximum diameter of 20 mm. This difference again brings into light the fact that waste rock materials are difficult to characterize due to the material heterogeneity and presence of coarse particles in the matrix (Yazdani *et al.* 2000).

The coarse and well graded particle size distribution creates challenges when it comes to collecting representative samples. Also, it seems that the waste rock material may be slightly unstable with finer particles moving during hydraulic conductivity tests. As for the WRC, the lack of appropriate methods for determining this property for coarser materials limits the capacity for an appropriate characterization (work is underway to investigate this aspect further).

4. NUMERICAL MODELING

Using the parameters and functions obtained in the field and in the lab, some numerical models were constructed. The objective of these models was to better understand the flow of water within waste rock piles by studying cases with specific characteristics. Several cases were evaluated and a few a presented below (see Martin 2003 for more details; see also Fala *et al.* 2003 for different waste rock dumps configurations). The basic features of the modeled cases shown here are given in Table 5 below. The finite element based software SEEP/w (version 5.17) developed by Geo-Slope International was used to complete the numerical models.

Table 5. Basic features of the various numerical models illustrated below.

Model	Features
S-1	Base case scenario
S-3	Surface sloped 5% towards the outside of the pile
S-6-2	Recontoured waste rock pile covered with a "Store, Divert and Release" (SDR) cover

Model S-1

Model S-1 was based on a bench of the waste rock pile at the Goldstrike Mine. It was simplified for modeling. A schematic view is shown in Figure 5. The height of the bench is 36 meters with a slope angle of 1.5H:1.0V.

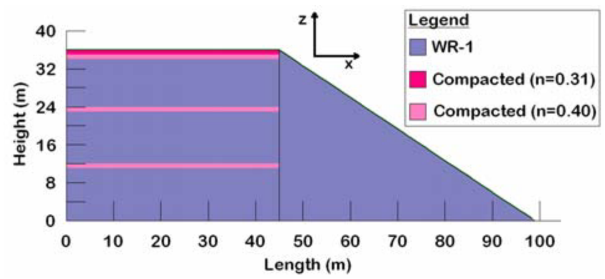

Figure 5. Model S-1.

Most of the waste rock dump is composed of WR-1 material with properties defined in section 3. The layers found at 12 m, 24 m and 36 m represent compacted layers that would have been created as the waste rock dump was being constructed. The WRC of these compacted layers are given in Figure 6 and the unsaturated hydraulic conductivities curves are given in Figure 7. The WRC of these materials were measured in Tempe cells using waste rock materials with a maximum diameter of 5 mm, which were then smoothed and average using the software RETC (van Genuchten *et al.* 1991) with the van Genuchten (1980) equation and two porosities: 0.31 for the most compacted surface layer and 0.4 for the compacted intermediate layer. The unsaturated hydraulic conductivity curves were predicted using the Mualem (1976) – van Genuchten (1980) model.

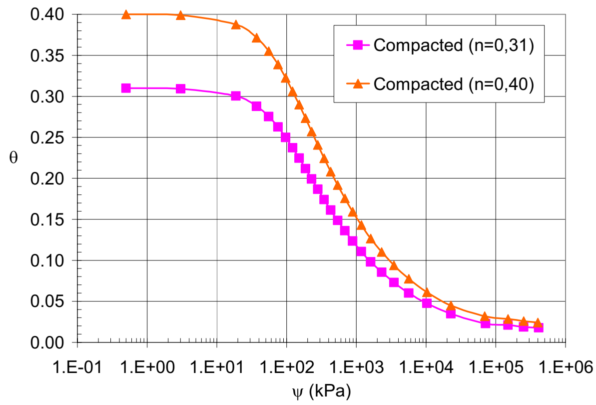

Figure 6. Water retention curves of the compacted materials in the modeled waste rock dumps.

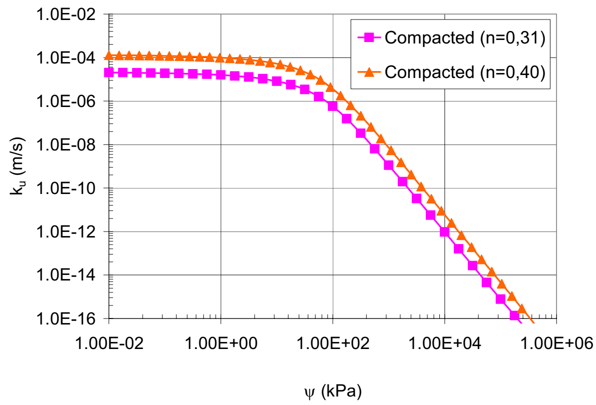

Figure 7. Unsaturated hydraulic conductivity curves of the compacted materials in the modeled waste rock dumps.

An infiltration function is applied at the surface of the waste rock dump, and the model drains from the toe of the dump. The infiltration corresponds to three days of precipitation with an intensity of 9.07×10^{-7} m/s followed by fourteen days of drainage (no precipitation or evaporation). This corresponds to applying for 3 consecutive days a 24 hour storm each with a return period of 100 years. Similar conditions were used by Zhan *et al.* (2002) to model the efficiency of the cover system placed on the leach pad at the Goldstrike Mine. The x-axis and y-axis of the model are assumed to be no-flow boundaries. These are the boundary conditions that have been applied for all the models.

Figure 8 shows the isocontours of volumetric water content following the 72 hour storm (a) and the 14 day drainage period (b).

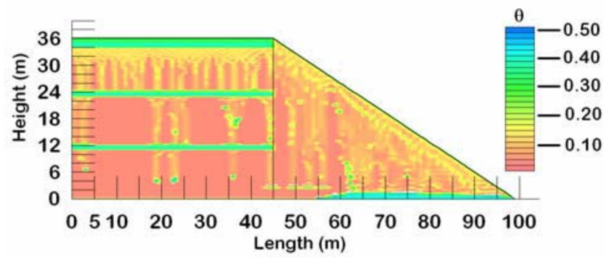

Figure 8 a). Volumetric water content (θ) isocontours for model S-1 following the 72 hour storm.

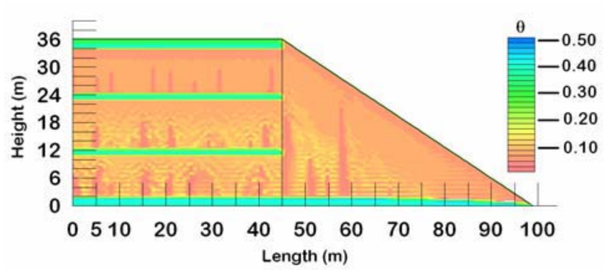

Figure 8 b). Volumetric water content (θ) isocontours for model S-1 following the 14 day drainage period.

In Figure 8a, it can be seen that the wetting front has reached a depth of about 6 meters on the horizontal surface, and of about 2 meters on the slope. Following the drainage period (Figure 8b), the wetting front is more diffuse but is found throughout the waste rock pile. This indicates that when a large precipitation event occurs, water can flow fairly easily inside the pile. If the material were to be acid generating, the presence of water and air in the pores favors generation of acid mine drainage. Because of their higher water retention capacity, the compacted layers located in the waste rock dump retain more water following a storm, until the water entry value of the uncompacted waste rock is attained at the compacted/uncompacted waste rock interface (water is then released deeper inside the pile).

In Figure 8a, some localized flow (somewhat similar to the fingering phenomenon) is observed. This occurrence has also been seen in results presented by Fala *et al.* (2003) and Fala (2002). The localized (unstable) flow seems to be caused by model size and number truncations in the software. Because of the steep slopes of both the WRC and the unsaturated hydraulic conductivity curve, a small change in suction may cause large changes in volumetric water content (θ) or unsaturated hydraulic conductivity (k). However, even though this is a numerical artifact, it is expected to mimic (in a broad, non local, sense) the physical phenomenon on unsaturated flow in such heterogeneous media.

Model S-3

Model S-3 is based on model S-1. The only difference is that the “horizontal” surface on top of the pile is sloped 5% towards the outside of the dump (Figure 9). The objective of this model is to evaluate the effect of a slope on the flow of water within the waste rock pile, in part to confirm some of the results obtained by Fala *et al.* (2003).

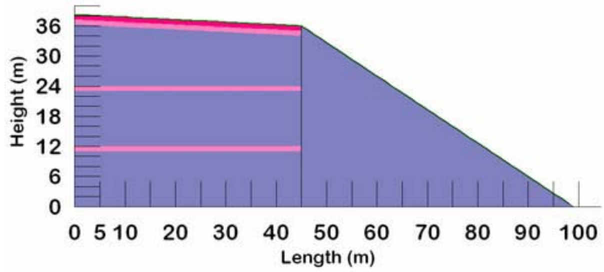

Figure 9. Model S-3.

Figure 10 shown below gives the volumetric water content contours after the 72 hour storm.

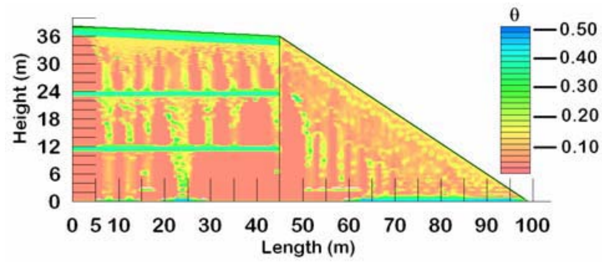

Figure 10. Volumetric water content (θ) isocontours for model S-3 following the 72 hour storm.

As expected, the sloped surface limits the infiltration into the deeper waste rock below the compacted surfaces. In this case, water starts to penetrate into the waste rock dump below the compacted layer about 6 meters from the y-axis. This point is known as the Down Dip Limit (DDL) and occurs in a slope, when the suction at the interface between the compacted and the uncompacted waste rock becomes equal to the water entry value (ψ_w or WEV) of the uncompacted waste rock. More information on this phenomenon can be obtained in Bussière (1999), Apithy (2003) and Bussière *et al.* (2003). It is important to state that in this case, no runoff was allowed on the top of the pile. If this were the case, there could have been less water flowing into the waste rock pile.

Model S-3 highlights that the infiltration of water inside waste rock dumps is greatly influenced by the slope of the surface of the pile, and that a surfaced sloped towards the outside of the dump can be beneficial as it will limit the amount of water that reach the core of the dump (Fala *et al.*

2003) which ultimately will limit the amount of water seeping through the bottom of the pile that will need to be managed.

Model S-6-2

Model S-6-2 presents a recontoured waste rock dump that has been covered with a "Store, Divert and Release" (SDR) cover. This cover works on the principle that, in a semi-arid climate, the precipitation events are usually of short duration and followed by long periods without rainfall. This allows lateral drainage (and evaporation, although not modeled with this software) of the water stored in the cover. Since acid mine drainage will occur if sulfidic materials are in contact with both water and oxygen, limiting one of these elements would inhibit the acid generation. The SDR cover limits water ingress into the waste rock materials, which are usually highly unsaturated (Zhan *et al.* 2001; Zhan *et al.* 2002; Bussière *et al.* 2003).

Model S-6-2 consists of a 36 meter bench of a waste rock dump with a slope recontoured to an angle of 2.5H:1.0V (from 1.5H:1.0V initially). The SDR cover is composed of 1.2 m (4 feet) of Carlin material (Figures 3 and 4). This is similar to the cover that was installed on the leach pad at the Goldstrike mine (Zhan *et al.* 2001; Zhan *et al.* 2002). Figure 11 shows model S-6-2.

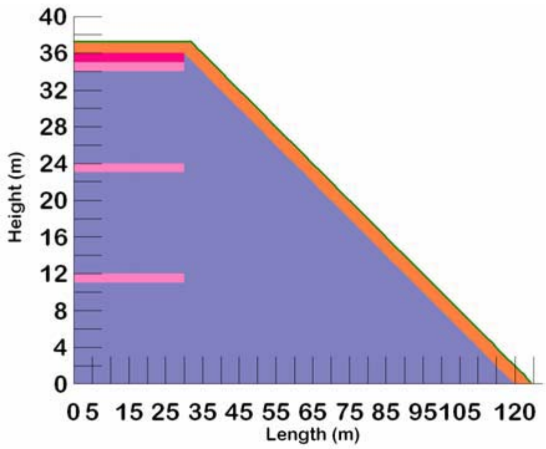

Figure 11. Model S-6-2 (note the vertical exaggeration).

The rest of the pile is composed of the WR-1 material and of the compacted layers (as defined is model S-1). The boundary conditions are the same as with model S-1.

Figure 12 gives the volumetric water content contours after the 14 day drainage period. It shows that there is no water infiltrating into the waste rock dumps following the modeled storm and the drainage period. This cover system works because the suction at the interface between the cover material and the waste rock always stays higher than the water entry value of the waste rock for the modeled period. Other factors that influence the effectiveness of such a cover system are the thickness of the cover, the material properties (e.g. AEV and WEV of both the waste rock and the cover material) and the slope length (Apithy, 2003).

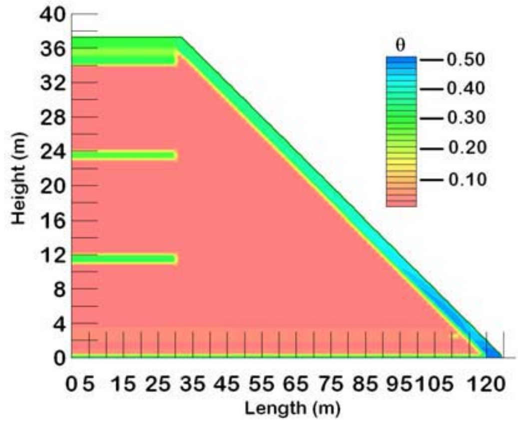

Figure 12. Volumetric water content (θ) isocontours for model S-6-2 following the 14 day drainage period.

In a companion paper (Martin *et al.* 2005), different cover configurations will be presented to illustrate the influence of the material properties on the cover efficiency.

5. CLOSING REMARKS

Characterization of waste rock and waste rock piles is a complex task. When characterizing a pile it is necessary to take into account the presence of coarse rubble zones, compacted layers, and other heterogeneities. The large amount of coarse particles influences the properties of the material that can be measured in the laboratory. All of these factors impact on the flow of water into the waste rock dumps, as seen in the numerical models shown in this paper.

6. ACKNOWLEDGEMENTS

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