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THE HYDROGEOLOGY OF WASTE ROCK DUMPS AND A MECHANISM FOR UNSATURATED PREFERENTIAL FLOW

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ABSTRACT

The ability to predict the rate at which contaminants flow to the environment from unsaturated, heterogeneous waste rock piles requires a better understanding of the physical and hydrogeologic characteristics of the waste rock pile. In particular, the mechanisms governing preferential flow in unsaturated environments need to be determined.

Key results of a multi-phase research program between Placer Dome Canada Inc., Golden Sunlight Mines Inc. and the Unsaturated Soils Group (USG) at the University of Saskatchewan are presented in this paper. The research program consisted of a detailed field and laboratory program to characterize waste rock material followed by a column study and a numerical modelling program which was designed to investigate possible mechanisms for preferential flow in layered, unsaturated environments.

The waste rock piles contained a highly-structured, steeply-dipping system of waste rock layers defined by changes in grain size. Coarse and fine-grained waste rock layers containing significantly different water contents were found adjacent to each other posing the possibility of preferential flow within the pile. Subsequent column studies and numerical modelling showed that in unsaturated, vertically-layered systems, liquid water may be transported preferentially through fine-grained rather than coarse-grained material. The development of this type of preferential flow is a result of changes in the hydraulic conductivity of the materials with increasing matric suction. The coarse-grained waste rock was found in the laboratory program to be incapable of retaining water under applied values of matric suction causing a rapid decrease in the unsaturated hydraulic conductivity. The fine-grained waste rock, however, was capable of retaining water and therefore maintained a higher unsaturated hydraulic conductivity under applied values of matric suction. This results in preferential flow occurring through the fine-grained layers rather than through the coarse layers as is often presumed.

Key words: *waste rock, unsaturated, matric suction, hydraulic conductivity, preferential flow*

INTRODUCTION

One of the most difficult problems in predicting seepage and the transport of contaminants through geologic structures is predicting the potential for preferential flow paths. Preferential flow paths may develop where particular areas of a geologic profile become more conductive than the surrounding material. There are many different terms which are cited in the literature to describe preferential flow through soils. These terms include macro-pore flow, short-circuiting, fingering and funnelling (Luxmoore, 1991). Peterson *et al.* (1966) and Whiting (1985) suggest that waste rock piles contain large, open channels which facilitate the flow of liquid water through the pile. References to preferential flow paths in waste rock piles are common in the literature, but few provide quantitative descriptions of the material through which the preferential flow occurs. Robertson and Barton-Bridges (1990) interpreted highly oxidized, fine-grained material surrounded by fresh grey waste rock as evidence of preferential oxidation within the fine layers. Kent and Johnson (1993) and Dawson *et al.* (1995) cited reduced pore-water pressures in fine-grained layers of mine waste as a potential source of slope instability. Many existing models attempt to predict the onset of acidic drainage and the resulting quality of leachate from waste rock piles. The vast majority of these models display limited knowledge regarding moisture movement within unsaturated, heterogeneous environments such as waste rock piles (Herasymuik, 1996). In addition, few field and laboratory measurements have been made which could be used to validate existing and future models. In assessing moisture movement in waste rock piles, consideration must be given to the configuration and construction of waste rock piles, the mineralogical composition of the parent rock, the dominant weathering processes which occur within the waste rock piles and the climatic conditions of each mine site.

In 1994, Placer Dome Canada Inc. and the Unsaturated Soils Group (USG) at the University of Saskatchewan initiated a multi-phase research program to investigate the hydraulic properties and moisture migration pathways found in the east waste rock pile at Golden Sunlight Mine (GSM). Phase I consisted of an extensive field investigated which consisted of logging and sampling structures within the waste rock pile. Phase II involved data reduction and laboratory analysis of the sampled waste rock. Phase III consisted of column studies followed by numerical modelling to investigate possible mechanisms for preferential flow in layered, unsaturated waste rock.

The research program was initiated to capitalize on a unique opportunity provided by a massive earth movement deep beneath the existing 100 million ton waste rock pile. To stabilize the pile, approximately 15 million tons of waste rock were excavated in a series of 18 m lifts.

BACKGROUND

Golden Sunlight Mine

Golden Sunlight Mine is a large, open pit, gold mine located in southwest Montana (Figure 1). The waste rock piles have high wedge-dump and terraced-dump configurations and were constructed by end-dumping waste rock in several lifts. The climate in the area is semi-arid and inter-mountain with 243 mm of precipitation per year occurring mostly as rainfall.

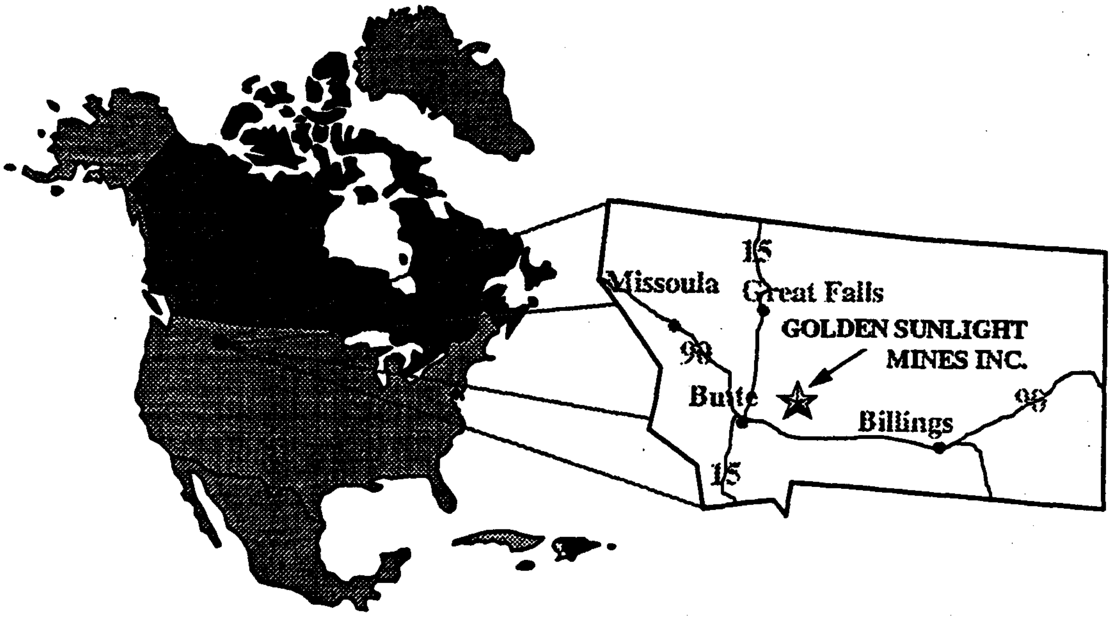


Figure 1: Site location of Golden Sunlight Mine

METHODOLOGY

Field Investigation

Waste rock was removed from the existing pile in a series of 18 m high benches. After the removal of each bench, the shovels were lowered approximately 18 m to begin excavation of the next level. Twenty-nine test pits were excavated, each 3 - 4.5 m in depth . The test pits were located along established transect lines. For safety and accessibility reasons, the field program was conducted on the bench located above the working shovel. Once the shovel began to excavate the next level, the transect lines were re-established on the bench above and the test pit program continued. A standard logging and sampling procedure was used in each test pit.

Within each test pit, layers which had been formed by the end-dumping process were visually logged with respect to mineralogic components, general grain sizes, texture, structure, matrix quantity and quality, state of oxidation/weathering, colour, strike, dip and any other special features. Samples of each visually described layer were gathered and shipped to the University of Saskatchewan for further laboratory analysis. *In situ* measurements of water content, matric suction, temperature and relative humidity were also taken (Herasymuik, 1996).

Data Reduction and Laboratory Analysis

The collected field data was compiled, focusing on the construction history, internal structure and distribution of moisture within the pile. Field logs were created using field notes and sample records. Cross-sections were constructed from as-built drawings to document the dump profile and construction history. The location of the test pits relative to the crest and toe locations for each year enabled the age of the waste rock material to be determined from each test pit. Gravimetric water contents were then correlated with the constructed cross-sections and were used to document the distribution of moisture within the pile.

The laboratory program involved classifying the sampled waste rock and determining basic hydrogeologic properties which included;

- grain-size distribution,
- paste pH,
- specific gravity,
- soil-water characteristic curves,
- saturated hydraulic conductivity.

The soil-water characteristic curve is a hydraulic property which is unique to every soil type. It describes the storage capability of a material and defines the amount of water which will remain in the pores under various applied matric suctions. Large pressure plates, utilizing the same principles as standard small pressure plates were used to measure the soil-water characteristic curves (SWCC) for representative samples. The large pressure plate is capable of handling coarse waste rock samples greater than 3 kg in mass and allows for a more representative soil-water characteristic curve to be established.

The hydraulic conductivity function describes the ability of a material to transport water under various applied matric suctions. Saturated hydraulic conductivity values were determined for representative samples. The unsaturated hydraulic conductivity function was predicted using a curve fitting program which uses the measured soil-water characteristic curve and saturated hydraulic conductivity (Fredlund *et al.*, 1994).

Column Studies and Numerical Modelling

Field observations indicated that the waste rock pile was highly structured with steeply-dipping layers. Column studies were proposed as a method of investigating the mechanisms for preferential flow through stratified waste rock layers. Preliminary modelling was completed on both a vertically layered system and a steeply inclined system. The results indicated that the potential for preferential flow existed in both environments. The final column design of a vertically layered column removed the possibility of gravity induced flow between the two materials.

Figure 2 is a schematic diagram of the rectangular column which measured 15 cm x 30 cm x 140 cm. The column was constructed out of clear plastic and allowed two different materials to be placed side by side in a series of lifts, separated by a thin metal cutoff. The cutoff could then be lowered through the base of the column resulting in contact between the two materials located above the height of the cutoff. The purpose of the cutoff was to determine flow partitioning with infiltration depth. Water flowing through the material above the cutoff was free to transfer between materials, however, below the cutoff horizontal flow was restricted.

A "rain machine" fed by a peristaltic pump connected to two constant head reservoirs was used to apply a range of rainfall fluxes. A uniform flux distribution over the surface of the column was achieved using hundreds of small diameter tubes which were connected to the constant head reservoirs. Separate drainage systems on each half of the column enabled discrete collection of the resulting discharge.

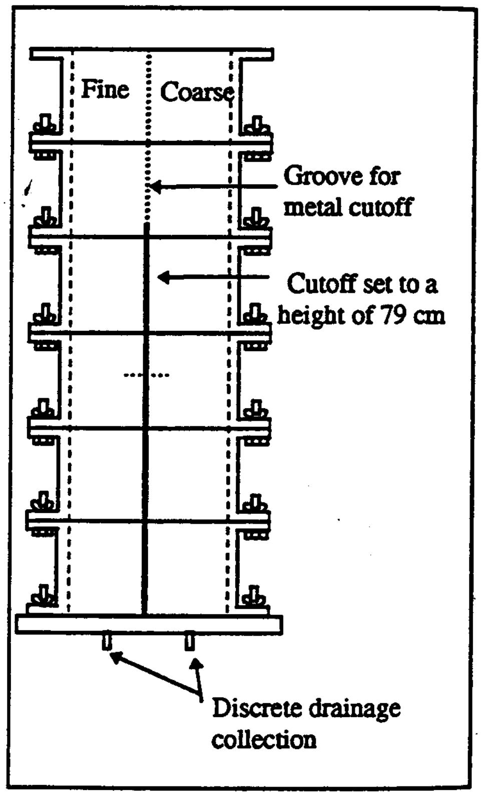


Figure 2: Column design

In the experiment, two separate materials were placed adjacent to each other in the column. In total , two column configurations were setup. In the first configuration, a fine Beaver Creek sand and a medium silica sand were placed adjacent to each other to a total height of 114 cm. The hydraulic properties for these materials had previously been determined (Wilson, 1990; Bruch, 1993; Swanson, 1995). For the first series of tests, the cutoff was adjusted to heights of 79 cm, 59 cm, 39 cm, 14 cm and 4 cm. The second material configuration involved two gradations of waste rock from GSM, one a fine-grained material (TP5GS1) and the other a modified coarse-grained material, (TP6GS5, modified). Herasymuik (1996) determined that the coarse waste rock gradation did not contain enough fine material to fill the inter-particle voids. As a result, large voids remained in the waste rock and the transport of liquid water was dominated by the coarse fraction. To avoid settlement of the fines and a non-uniform gradation within the column, the coarse gradation was modified to remove the fine fraction which passed the #70 (0.21 mm) sieve. For the waste rock configuration, the total column height was increased to 136 cm and one cutoff height of 36 cm was used.

The flow of water in a saturated soil is most often described using Darcy's law. The rate at which water flows through a soil is proportional to the hydraulic head gradient and is written as follows:

$$q_{sat} = -k_{sat}\, dh/dl$$

where,

q_{sat} = flow rate of water, (cm/s),
k_{sat} = hydraulic conductivity, (cm/s),
dh/dl = hydraulic head gradient, (cm/cm).

The hydraulic conductivity of an unsaturated soil is not constant but becomes a function of matric suction, $k(\Psi)$. In an unsaturated soil, under a hydraulic gradient of one, the flow rate of water through the soil is equal to the hydraulic conductivity and can be significantly less than the saturated rate.

For the column experiment, four uniform fluxes ($q_{applied}$), were applied over the surface of the column for each cutoff height. Two of the applied rates were known to slightly exceed the saturated flow rate, q_{sat}, of the fine layer and two were applied at reduced rates. Once it was determined that the inflow rate was equal to the cumulative outflow rate, the resulting discharge was measured and the percentage of flow transported through the coarse material was compared to the amount transported through the fine material. The applied rainfall flux was then reduced and the procedure was repeated for each contact length. Once the laboratory experiment was completed, numerical modelling was performed using the 2-D finite element modelling package SEEP/W (Geo-Slope, 1995).

PRESENTATION AND DISCUSSION OF RESULTS

Field Observations

The waste rock pile at Golden Sunlight Mine was constructed by end-dumping waste rock from several platform elevations. During the field program, Herasymuik (1996) observed that this method of construction strongly controlled the structural orientation within the pile. Waste rock layers were found to be dipping at angles equal to the angle of repose of the material (approximately 40°). The strike angles were consistent with the edge of the top surface from which the material was end-dumped.

The structure of the layers was defined by colour and/or grain size differences. Figure 3 shows an example of the dipping, layered structure which was visible on an 18 m high excavated bench of the waste rock dump. The layer thickness within the pile varied considerably, ranging from thin lenses of 10-20 cm to layers in excess of several meters.

Within a single layer the material could consist of a single rock type or be composed of a combination of several rock types. The potential variation in grain sizes between adjacent layers was found to be extreme, with coarse "rubble layers" exhibiting large open interparticle voids in sharp contact with fine layers containing significant percentages of silt and sand which infilled the interparticle spaces. The layers also dipped at an angle consistent with the overall structure of the pile. The presence of a basal coarse layer was confirmed to exist at the base of the pile as a result of material segregation during the end-dumping procedure.

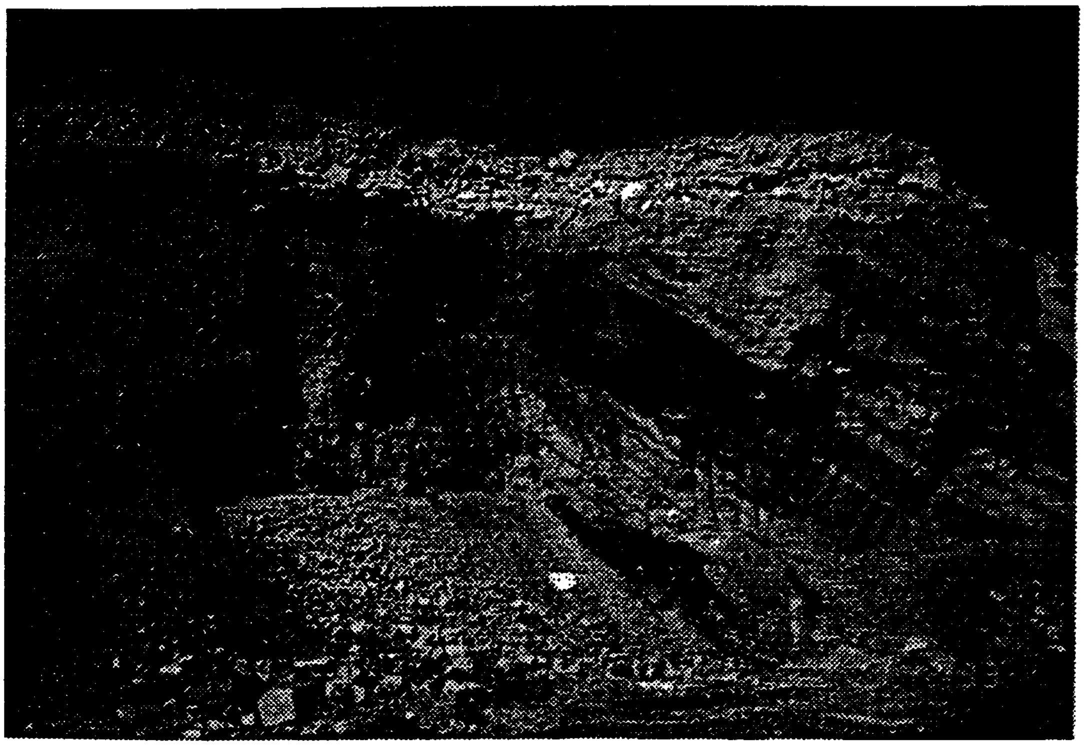


Figure 3: Photograph showing a highly defined, layered structure within the waste rock pile (Herasymuik, 1996).

Laboratory Analyses of Waste Rock Samples

The waste rock samples from the test pits were classified by grain size distribution. The classification criteria was based on the percentage of material passing the #4 (4.75 mm) sieve. Waste rock was classified into six groups, <10%, 10%-19%, 20%-29%, 30%-39%, 40%-49% and > 50% passing the #4 sieve. Figure 4 shows grain size distributions for five different materials. The percentage of material passing the #4 sieve for each of the five materials is as follows: TP5GS1 - 57%, TP7GS3 - 52%, TP18GS5 - 47%, TP6GS5 - 39% and TP6GS4 - 29%.

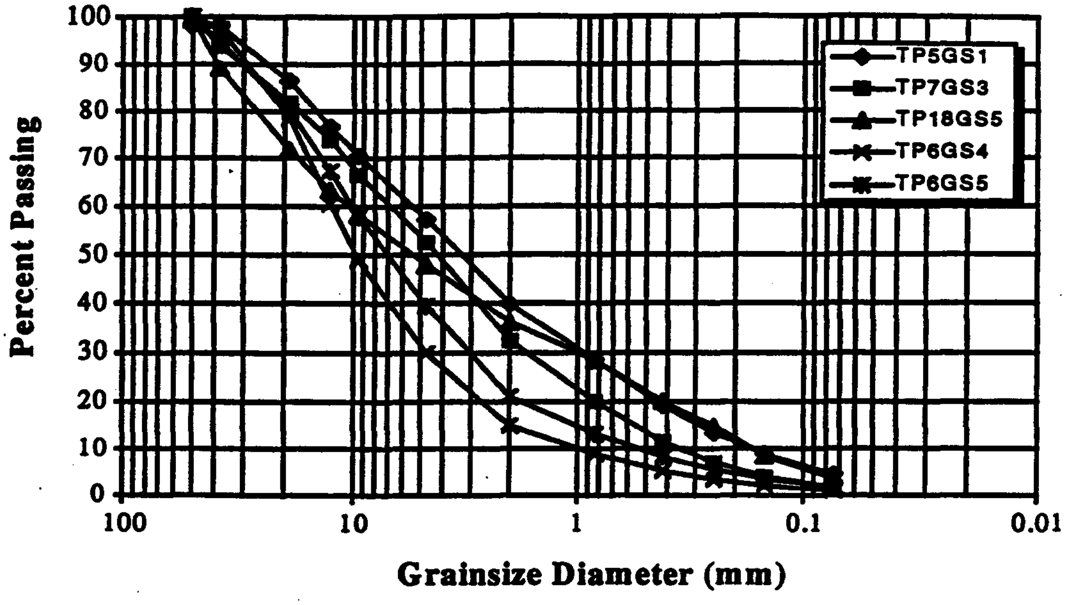


Figure 4: Grain size distribution curves for samples chosen for large diameter pressure plate testing (Herasymuik, 1996).

Soil-water characteristic curves were determined for a single sample from each classification group. Of these samples, saturated hydraulic conductivities (k_{sat}) were determined for those containing greater than 40% fine fraction. For the samples which contained less than 40% fines, k_{sat} was assumed to be 1.0 x 10^{-1} cm/s based on documentation found in the literature. The corresponding soil-water characteristic curves as determined from the large pressure plate apparatus are presented in Figure 5 and reveal two general types of waste rock. Waste rock samples containing a fine fraction of greater than 40% passing the #4 sieve, were capable of retaining water under negative pore-water pressures and are presented as samples TP5GS1, TP7GS3 and TP18GS5. Waste rock samples which contained less than 40% passing the #4 sieve are presented as samples TP6GS5 and TP6GS4 in Figure 5. The important characteristic of these curves is a very small air entry value. The materials drain under small values of matric suction and show little capacity to retain water under negative pore-water pressures.

The predicted hydraulic conductivity functions for the samples tested are presented in Figure 6. The curves clearly illustrate the difference between the two material types. The waste rock samples which are capable of retaining water under negative pore-water pressures retain a higher unsaturated hydraulic conductivity. Materials which do not contain a significant fine fraction (i.e., TP6GS5 and TP6GS4) drain rapidly under negative pore-water pressures and therefore experience a rapid decrease in hydraulic conductivity.

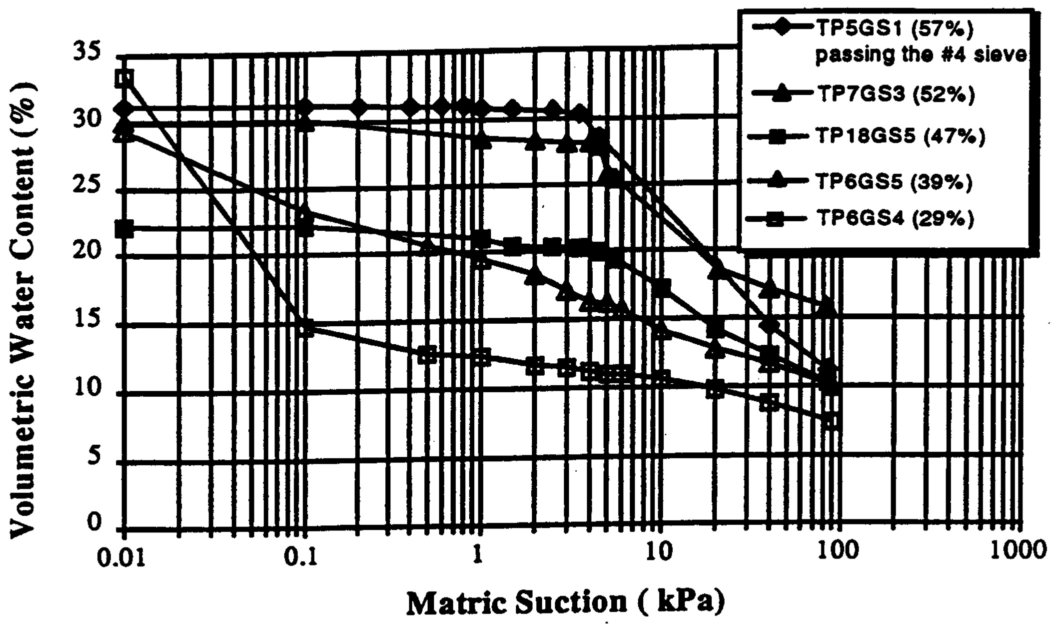


Figure 5: Soil-water characteristic curves (Herasymuik, 1996).

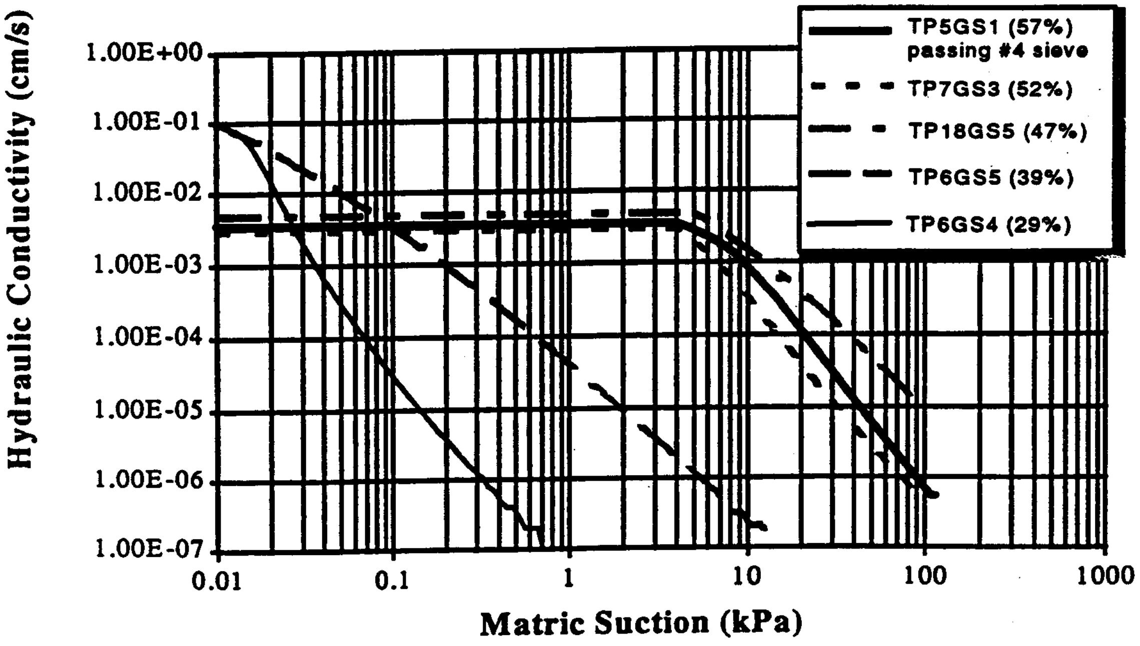


Figure 6: Hydraulic conductivity functions (Herasymuik, 1996)

Column Experiment and Numerical Modelling Results

Series 1: Beaver Creek Sand and Medium Silica Sand

The soil-water characteristic curve defines the amount of water which will remain in the pores under applied matric suctions. The hydraulic conductivity function describes the rate at which water will be transported under applied matric suctions. The rate at which water will flow through an unsaturated soil depends in part on the degree of saturation of the soil. Simply stated, water prefers to flow where water exists. Under unsaturated conditions, a fine-grained material may become more conductive than a coarse-grained material even though the saturated hydraulic conductivity of the fine may be lower.

The hydraulic conductivity function and the soil-water characteristic curves for the Beaver Creek and medium silica sand are shown in Figure 7. The silica sand has an air-entry value less than 1 kPa and a storage potential which drops rapidly after this value is exceeded. The Beaver Creek sand has a higher air-entry value (3 kPa) and does not drain as rapidly under applied suctions. The saturated hydraulic conductivities of the Beaver Creek sand and the silica sand are 8.89×10^{-4} cm/s and 3.0×10^{-1} cm/s respectively. The hydraulic conductivity curves for the two materials cross at a matric suction value of approximately 1.4 kPa. At suctions less than 1.4 kPa, the coarse material is more conductive than the fine material; however, at suctions exceeding 1.4 kPa, the fine material has a higher hydraulic conductivity. In Figure 7, two of the four applied fluxes (q_1 and q_4) which were applied to the surface of the column are superimposed on the hydraulic conductivity function. As previously stated, under a hydraulic gradient of one the flux rate transported through a soil is equal to the hydraulic conductivity. The highest flux rate applied, $q_1=1.33 \times 10^{-3}$ cm/s was slightly greater than the q_{sat} of the fine material, and the lowest flux rate applied, $q_4= 3.68 \times 10^{-4}$ cm/s, was less than the q_{sat} of the fine material.

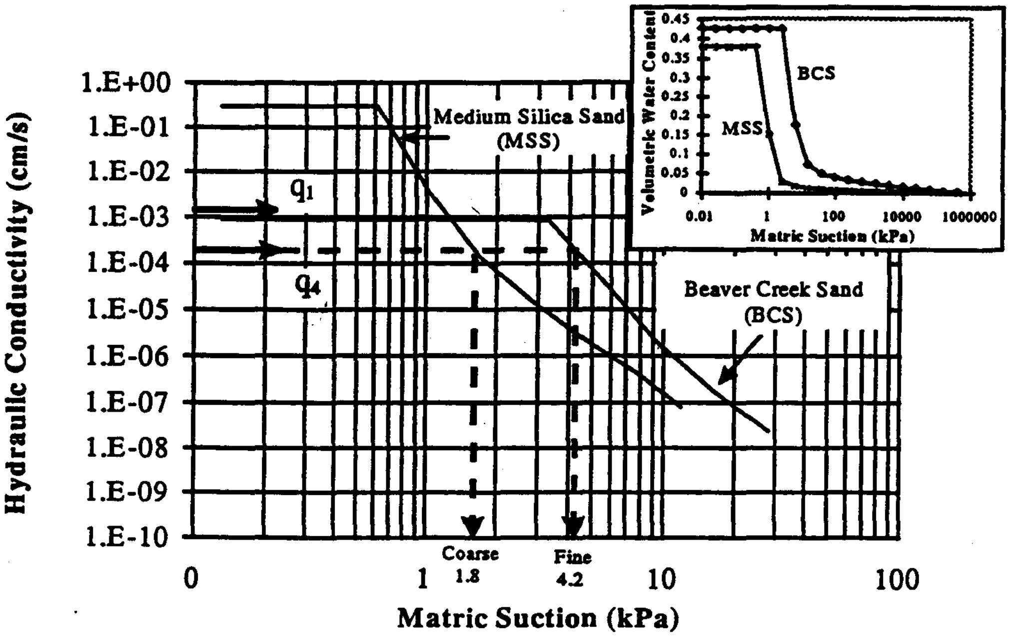
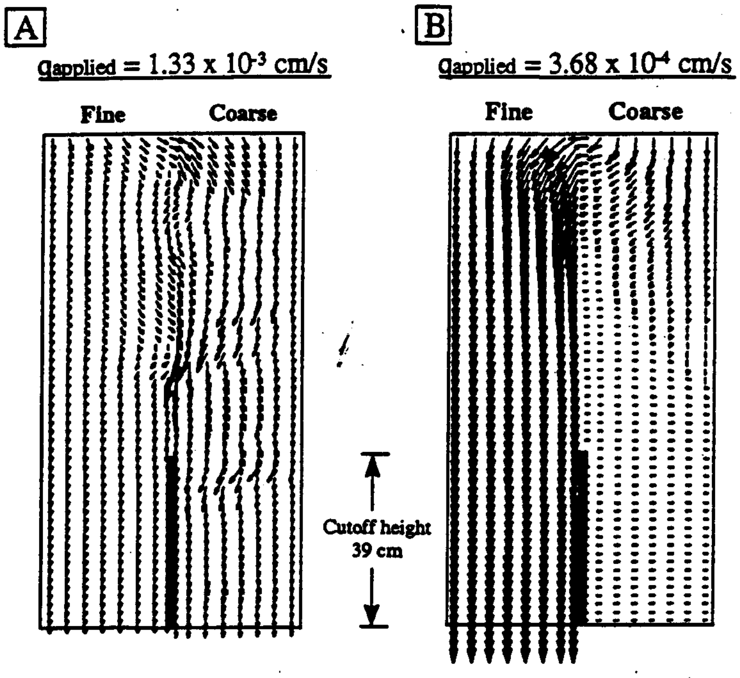


Figure 7: Hydraulic conductivity and soil water characteristic curves for Beaver Creek sand (fine) and medium silica sand (coarse), (Newman, 1997).

The results from the column experiment and numerical modelling program show that when $q_{applied} > q_{sat(fine)}$, water flows preferentially through the coarse material as indicated by the arrows shown in Figure 8(a). Under steady-state conditions, pore-water pressures at the surface are reduced in the fine material as the pores become water filled. The coarse material however still experiences negative pore-water pressures under the applied flux. Between matric suctions of 0 to 1.4 kPa, the coarse material is more conductive and water which enters the fine material flows preferentially toward the coarser material.



Flow partitioning: Fine 35%
Coarse 65%

Flow partioning: Fine 97%
Coarse 3%

Figure 8: SEEP/W results for the fine and coarse sand configuration under two applied flux rates (Newman, 1997).

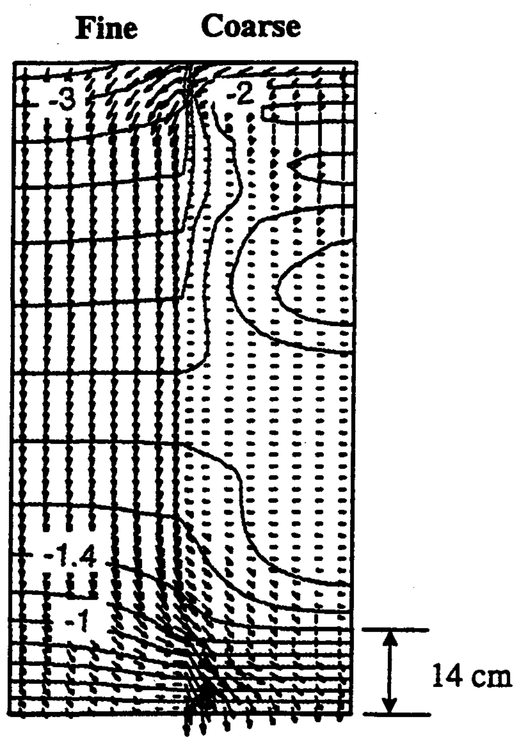
When $q_{applied} < q_{sat(fine)}$, water flows preferentially through the fine material (Figure 8(b)). Under an applied flux equal to q_4, if the column was filled with a homogeneous mixture of either the fine or the coarse sand, the suctions which would occur in the column would be either 1.8 kPa (coarse) or 4.2 kPa (fine), as is shown in Figure 7. In a vertically layered, infinitely long column under steady-state, the total head values which would exist at any elevation would be the same. Consequently, the matric suctions within the two materials would also be the same and would be equal to some value between the two extremes (i.e., 1.8 kPa and 4.2 kPa) This equilibrium suction however, is still larger than the cross-over condition of 1.4 kPa and so the material which transports the majority of the water is the one exhibiting the greater conductivity. In this case, the material with the higher conductivity is the fine material.

The cutoff height for this analysis was 39 cm which provided an interactive length of 75 cm. In the laboratory under an applied flux of $q_1 = 1.33 \times 10^{-3}$ cm/s, 30% of the flow which entered the fine layer was transferred into the coarse layer before a depth of 75 cm. This resulted in a partitioning of the flux as follows: 35% (fine) and 65% (coarse). For an applied flux of $q_4 = 3.86 \times 10^{-4}$ cm/s, partitioning resulted in 97% of the applied flux moving through the fines while 3% moved through the coarse side. Below a depth of 75 cm, water which was present in either layer was forced to remain in that layer. Numerical modelling provided the same results.

Both laboratory and numerical modelling results showed that a longer contact length between the two materials allowed more lateral flow of water with depth. However, the results from the 3 cm cutoff height configuration (111 cm of total contact length) appear contradictory. Virtually 100% of the water discharged from the bottom of the coarse layer under all applied surface flux conditions. Numerical modelling confirmed this trend (Figure 9).

In both the column and numerical simulations a zero-pressure boundary condition was placed at the base of the column. As the water flowed towards the bottom, suctions had to reduce to satisfy this condition. The pressure contours plotted on Figure 9 highlight the point of re-crossover which occurred at an elevation of approximately 14 cm, corresponding to a pressure of 1.4 kPa. This is the crossing point of the two hydraulic conductivity functions in Figure 7.

$q_{applied} = 3.68 \times 10^{-4}$ cm/s



Flow partioning: Fine 20%
Coarse 80%

Figure 9: SEEP/W results showing re-crossover as suctions reduce at the base of the column (Newman, 1997).

Series 2: Fine and Coarse GSM Waste rock

Herasymuik (1996) determined the saturated conductivity of the fine and coarse GSM waste rock (TP5GS1 and TP6GS5) to be 3.4×10^{-3} cm/s and 1.0×10^{-1} cm/s respectively (Figure 6). The *in situ* values of hydraulic conductivity for the two waste rock materials used in the column study were significantly less than the reported results. The difference in conductivity may be a result of soil packing within the column. For a contact length of 100 cm and an applied flux of 5.15×10^{-4} cm/s, 18% of the water was transported through the fine material. Fourty-eight percent of the water flowed through the fines with an applied flux of 1.41×10^{-5} cm/s. At a flux of 5.56×10^{-8} cm/s, 65% travelled through the fine layer.

It is interesting to note that the annual net infiltrative flux for Golden Sunlight Mine was

SUMMARY AND CONCLUSIONS

Field results show that the waste rock pile contains a highly-structured, steeply-dipping system of waste rock layers defined by changes in grain size and/or colour. Column studies and numerical modelling show that in unsaturated, layered systems such as waste rock piles, liquid water may be transported preferentially through the fine-grained material rather than the coarse-grained material. This contradicts conventional theory for flow in waste rock dumps. This form of preferential flow is significant in that is may allow the waste rock pile to store water, increasing the potential for acid mine drainage. Increased oxidation of fine layers within waste rock piles could contribute to layers of decreased shear strength and possible slope failure within the pile.

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