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MECHANISMS FOR PREFERENTIAL FLOW IN VERTICALLY LAYERED, UNSATURATED WASTE ROCK

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ABSTRACT

In order to accurately predict the rate at which contaminants are released from unsaturated, heterogenous environments such as waste rock piles, information is required regarding the physical and hydrogeologic characteristics of waste rock. In particular, the development of preferential flow paths with waste rock piles needs to be considered.

Waste rock piles are highly-structured environments which contain steeply-inclined fine and coarse-grained layers frequently lying adjacent to one another. A laboratory column study which was developed to imitate this stratigraphy revealed that in an unsaturated environment, preferential flow may occur through the fine-grained layers rather than through the coarse layers as is often presumed.

RESUME

Pour prédire avec précision la vitesse d'échappement de contaminant des milieux non-saturés et hétérogènes tels que les stériles de roche, il faut connaître les caractéristiques physiques et hydrogéologiques des stériles. On doit surtout étudier le développement de pistes d'écoulement préférentiel à l'intérieur des piles de stérile.

Les stériles de roche sont des milieux très structurés contenant des couches fortement inclinées de roches fines et de grosses roches, souvent situées l'une à côté de l'autre. Une étude en laboratoire, conçue pour imiter cette stratigraphie, a démontré qu'en milieu non saturé, l'écoulement préférentiel peut se produire à travers les couches de roches fines, plutôt qu'à travers les couches de grosses roches comme on le suppose souvent.

INTRODUCTION

The ability to characterize water movement in unsaturated, heterogeneous waste rock piles requires that the mechanisms governing preferential flow in unsaturated environments be determined. The generic term 'preferential flow' is used to describe a condition where a particular area of a profile becomes more conductive than the surrounding material. It has been suggested in the literature that waste rock piles contain large, open channels which facilitate the flow of water through the pile (Peterson *et al.*, 1966 and Whiting, 1985). References to preferential flow paths in waste rock piles are common, but few citations 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 induced pore-water pressures in fine-grained layers of mine waste as a potential source of slope instability. There are numerous models which have been proposed in an attempt to predict the onset of acidic drainage and leachate quality from waste rock piles, but the vast majority neglect unsaturated moisture movement in heterogeneous environments (Herasymuik, 1996). There is also a lack of field and laboratory measurements which could be used to validate existing and future models.

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). The research program involved a field study, laboratory analysis and a column study followed by numerical modelling to investigate possible mechanisms for preferential flow in layered, unsaturated waste rock.

BACKGROUND

The research program was initiated to capitalize on a unique opportunity created by the reactivation of an ancient landslide located under the existing 100 million ton waste rock pile. It became necessary to excavate 15 million tons of waste rock in order to stabilize the massive earth movement.

Field Program and Laboratory Analysis

Golden Sunlight Mine, GSM, is a large, open pit, gold mine located in southwest Montana. The waste rock pile at Golden Sunlight Mine was constructed by end-dumping waste rock from several platform elevations. Herasymuik (1996) observed that this method of construction strongly controlled the internal structure within the pile. The potential variation in grain-sizes between adjacent layers were found to be extreme, with coarse 'rubble layers', with insufficient fine-grained material to fill interparticle voids in sharp contact with fine layers containing significant percentages of silt and sand. The thickness of the layers within the pile varied considerably, ranging from thin lenses of 10 to 20 cm to layers in excess of several meters. Near the surface of the dump, the fine-grained layers had elevated moisture contents while the coarse-grained layers remained relatively dry. Figure 1 shows an example of the layered, steeply-dipping system revealed on a working face during the excavation process.

Column Study

The presence of the steeply-dipping fine and coarse-grained layers lying directly adjacent to each other, suggested the development of possible preferential flow paths within the waste rock pile. A column study was developed to study the flow processes in these layers under controlled conditions.

FIGURE 1. Photograph showing a highly defined, layered structure within the waste rock pile (Herasymuik, 1996).

A rectangular column measuring 15 cm x 30 cm x 140 cm was constructed out of clear plastic (Figure 2). The column was designed to facilitate the placement of two materials, separated by a thin, metal cutoff which ran the length of the column. Once the column was assembled, the cutoff could be lowered to different elevations through the base, allowing the two materials to be in direct contact above the height of the cutoff. The cutoff was used to determine the percentage of flow partitioning which would occur with depth. Water flowing through the material above the cutoff was free to move between materials.

A 'rain machine' was used to apply a range of surface fluxes. The fluxes were evenly distributed over the surface of the column. Separate drainage systems located under each side at the base of the column enabled discrete collection of the resulting discharge.

Two configurations were used during the column study. The first consisted of a fine Beaver Creek sand (fine sand) placed adjacent to a coarse medium silica sand (coarse sand) over a total height of 114 cm. The hydraulic properties of both materials had previously been determined (Wilson, 1990; Bruch, 1993; Swanson, 1995). The cutoff was adjusted to heights of 79 cm, 59 cm, 39 cm, 14 cm and 4 cm. The second configuration involved two gradations of waste rock (fine and coarse grained) from GSM, with a total column height of 136 cm and a single cutoff height of 36 cm.

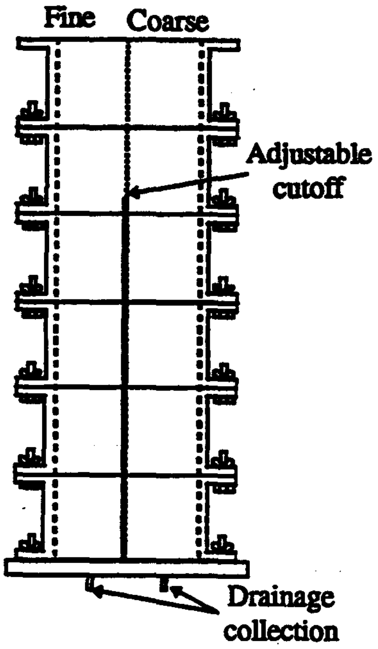


FIGURE 2. Column design (after Newman, 1997)

Four uniform fluxes ($q_{applied}$), were applied over the surface of the column for each cutoff height. Two of the applied rates slightly exceeded the saturated infiltration rate (q_{sat}) for the fine layer and two were applied at reduced rates. Once it was determined that the inflow rate was equal to the outflow rate, the resulting discharge was measured and the percentage of flow through each layer was compared. The applied 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).

THEORY

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:

$$q_{sat} = -k\ dh/dl \qquad \text{[Eq. 1]}$$

where,

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

however, in an unsaturated soil, the hydraulic conductivity is not constant but becomes a function of matric suction or degree of saturation. The flow rate through an unsaturated soil, under a hydraulic gradient of one, is equal to the hydraulic conductivity and can be significantly less than the saturated rate. Simply stated, water prefers to flow where water exists. Under unsaturated conditions, the hydraulic conductivity of a fine-grained material may be greater than that for a coarse-grained material even though the saturated hydraulic conductivity of the finer material may be lower.

COLUMN RESULTS

Configuration #1: Fine and Coarse Sand

The hydraulic conductivity function for the fine and coarse sand are shown in Figure 3. The coarse sand has an air-entry value less than 1 kPa and a hydraulic conductivity function which drops rapidly after this value is exceeded. The fine sand has a higher air-entry value (3 kPa) and does not drain as rapidly under applied suctions. The saturated hydraulic conductivity of the fine and coarse sand are 8.9×10^{-4} cm/s and 3.0×10^{-1} cm/s respectively. The hydraulic conductivity curves for the two materials cross at a matric suction of approximately 1.4 kPa. At suctions less than 1.4 kPa, the coarse material is more conductive than the fine material; while at suctions exceeding 1.4 kPa, the fine material has a higher hydraulic conductivity. In Figure 3, two of the four applied fluxes 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, q① = 1.33×10^{-3} cm/s, was slightly greater than saturated hydraulic conductivity of the fine material, and the lowest flux rate applied, q② = 3.68 x 10^{-4} cm/s, was less than the saturated hydraulic conductivity of the fine material.

The results from the column experiment and numerical modelling program show that when the applied surface flux, q①, is greater than the saturated hydraulic conductivity of the fine material water flows preferentially through the coarse material as indicated by the arrows shown in Figure 4(a). Under steady-state conditions, the pore-water pressures at the surface are reduced in the fine material as the pores become water filled. Under the same applied surface flux, the negative pore water pressures within the coarse material are 1.2 kPa. 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.

When the applied surface flux, q②, is less than saturated hydraulic conductivity of the fine material water flows preferentially through the fine material (Figure 4(b)). The reason for this change in flow path can be explained by examining the interaction of the hydraulic conductivity functions for the two materials (Figure 3). Under an applied steady-state flux equal to q②, a column filled with the fine sand would experience suctions equal to 4.2 kPa as indicated by the dashed line. In a column filled with the coarse sand under the same applied flux, the suctions would stabilize at 1.8 kPa under steady-state conditions. Within a vertically layered system where the two materials are in direct contact, the equilibrium suction which

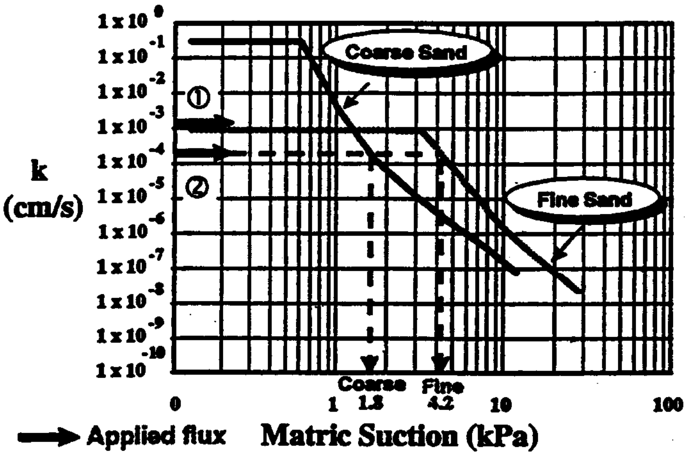
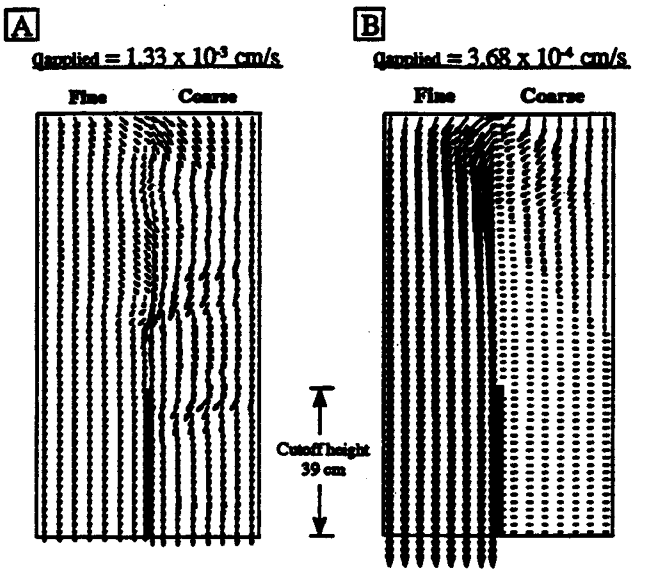


FIGURE 3. Hydraulic conductivity functions for the fine and coarse sand



Flow partitioning: Fine 35%
Coarse 65%

Flow partioning: Fine 97%
Coarse 3%

FIGURE 4. SEEP/W results for the fine and coarse sand configuration under two applied flux rates (Newman, 1997).

develops under the applied surface flux q②, is equal to a value somewhere between these two extreme values (i.e., 4.2 kPa and 1.8 kPa). The 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 which in this case is the fine material.

The cutoff height for the analysis presented in Figure 3 was 39 cm which provided an interaction length of 75 cm. In the laboratory under an applied flux of q① = 1.33 x 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 q② = 3. 68 x 10^{-4} cm/s, 97% of the applied flux was transported 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 (111 cm of total contact length) appear contradictory. Virtually all of the water discharged from the bottom of the coarse layer under all applied surface flux conditions. Numerical modelling confirmed this trend (Figure 5).

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 in Figure 5 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 3.

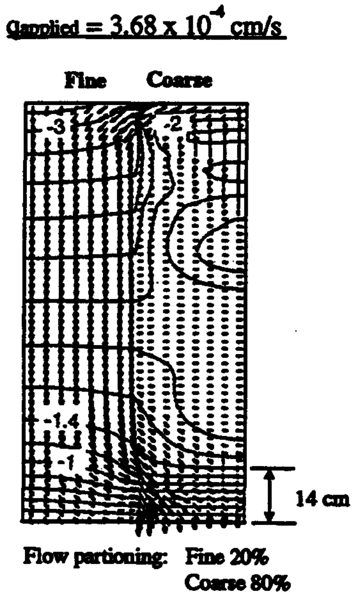


FIGURE 5. SEEP/W results showing crossover at the base of the column. (Newman, 1997).

Configuration #2: Fine and Coarse Waste Rock

The procedure described for the first column configuration was repeated using two gradations of GSM waste rock previously been hydraulically characterized by Herasymuik (1996). The hydraulic conductivity functions for these materials are shown in Figure 6. Percentages located next to each function indicate the quantity of material which was found to pass the #4 (4.75 mm) sieve.

The coarse waste rock did not have enough fine material to fill the interstitual voids and as a result, the large empty voids began to drain as soon as suctions were applied. This is reflected in the lack of an air entry value for the coarse material. The air entry value of the fine waste rock was measured to be approximately 4 kPa.

Herasymuik (1996) had determined the saturated conductivity of the fine and coarse GSM waste rock to be 3.4×10^{-3} cm/s and 1.0×10^{-1} cm/s respectively (Figure 6). The values of hydraulic conductivity for the two waste rock materials measured 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. Forty-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.

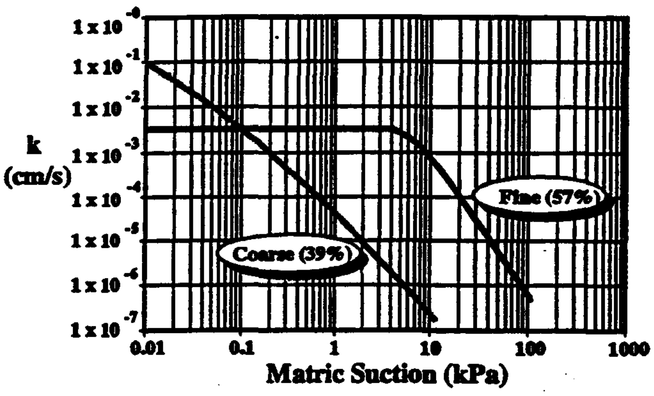


FIGURE 6. Hydraulic conductivity functions for fine and coarse waste rock (after Newman *et al*, 1997)

It is interesting to note that the annual net infiltrative flux in the waste rock piles at Golden Sunlight Mine was determined by Swanson (1995) to be .25 in/year or 2.01×10^{-8} cm/s. This value is still significantly less than the flux value needed to produce preferential flow through the fine material at Golden Sunlight Mine.

SUMMARY AND CONCLUSIONS

End-dumped waste rock piles, are comprised of highly-structured, steeply-dipping waste rock layers. The presence of coarse and fine-grained layers in sharp contact with each ~~other,~~ suggests the potential for preferential flow. Column studies and numerical modelling show that in unsaturated, layered systems such as waste rock piles, water may be transported preferentially through the fine-grained material rather than the coarse-grained material which challenges conventional thinking with respect to flow in waste rock dumps.

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