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## Abstract

The ability of engineers to predict seepage from unsaturated, heterogeneous environments requires a better understanding of the principles governing mass transport, particularly as it relates to flow along preferential pathways. Preferential flow paths exist where particular zones of a soil profile are more conductive than the surrounding material. Although there are many references regarding preferential flow in the literature, very few provide quantitative descriptions of the material through which the preferential flow occurs.

In 1994, the excavation of a large, unsaturated waste rock pile revealed the presence of a highly structured environment consisting of steeply dipping layers of fine and coarse material lying adjacent to one another. A laboratory column study followed by a numerical modelling program was designed in an attempt to investigate the mechanisms for preferential flow in this type of environment.

The results of the column study and numerical modelling program indicate that in unsaturated environments where fine and coarse vertical layers co-exist, liquid water may be transported preferentially through fine-grained rather than coarse-grained material as is often presumed. The development of this type of preferential flow is a result of changes in the hydraulic conductivity of the two materials with increasing suctions.

The occurrence of preferential flow in fine-grained material is a concern in many areas of geotechnical engineering including; slope stability and seepage analysis, contaminant transport and lysimeter design. This paper will present the theoretical basis for flow in unsaturated, layered environments. The experimental results and subsequent numerical analysis, which verify the theory, are also presented.

## Introduction

Waste rock piles are commonly constructed in mining operations during the removal of overburden. Infiltrating precipitation is transported through the waste rock and discharges as leachate at the bottom. The dissolved minerals and reaction products, which can be present in the leachate, pose an environmental hazard to the surrounding environment.

End-dumping waste rock is a popular construction method, which has been found to strongly control the internal structure of the pile [1]. At Golden Sunlight Mine (GSM) in Montana, USA, the end-dumped waste rock pile was found to consist of fine and coarse-grained layers, steeply dipping at angles consistent with the angle of repose of the material. The waste rock piles are generally unsaturated, and the interbedded, steeply layered structure results in a flow process, which is poorly understood. It has been suggested that the large, open channels facilitate the flow of water through the pile [2][3]. The GSM waste rock pile contained a wetting front where the moisture existed within the fine-grained layers and the coarse waste rock remained dry [1]. 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.

Moisture movement in vertically layered, unsaturated soils was initially studied by Horton and Hawkins [4] in 1965. Their work was intended to dispute conventional thinking, which believed that infiltrating rainwater percolated to the water table through the drained pores in the unsaturated soil and not through the pores which were fluid-filled. A circular column experiment was designed in which a coarse-grained material with large interstitual pores, (i.e., sand) was surrounded by a fine-grained material containing smaller interstitual pores, (i.e., sandy clay) as shown in Fig. 1. A length of plastic tubing extended upward from the bottom of the column and surrounded the coarse-grained material. The tubing length was adjusted throughout the study and was used to evaluate the depth that infiltrating water would penetrate the coarse material before transferring over to the fine material. A series of simulated rainfall events were applied to the surface of the coarse-grained material and the resulting effluent was collected separately from both the fine and coarse-grained material.

The results indicated that infiltrating rainfall, which was only applied to the coarse-grained material, transferred over to the fine-grained material over a relatively short distance. There was however, a seemingly contradictory result between two of the eleven column tests conducted. One column test used an applied rainfall rate of 76 mm and a plastic tubing length of 30 cm which allowed the two materials to be in direct contact over the top 122 cm of the 152 cm column. For this configuration, 100% of the applied precipitation transferred over to the fine-grained material before the top of the plastic tubing was reached. In a second test, the same surface flux was applied to a column where the material was allowed to interact for 150 cm of the 152 cm-long column, a tubing height of only 2 cm. Instead of 100% of the flow exiting from the fine-grained material, 100% of the flow was collected from the coarse-grained material. Horton and Hawkins [4] concluded that the infiltrating water must have flowed from the coarse material into the fine material at the top of the column and then transferred back to the coarse material at a depth greater than 122 cm, the elevation of the plastic tubing in the first column test. They speculated that the re-crossover likely occurred at the elevation where the coarse-grained material became tension saturated, approximately 20 cm up from the bottom, however, they did not have numerical modelling capability to confirm or correct their suspicions.

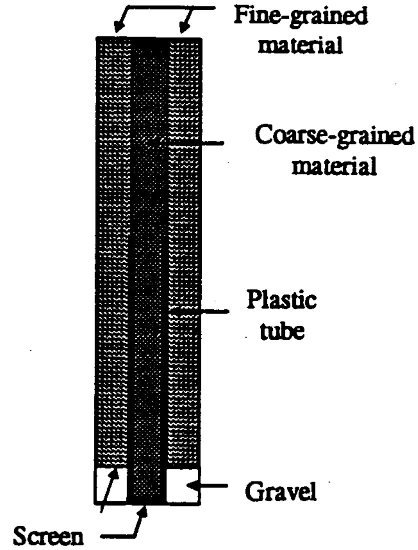


**Fig.1** Column design (after [4])

The presence of the highly stratified, fine and coarse-layered environment within the GSM waste rock pile, in conjunction with the discovery of elevated water contents within the fine-grained waste rock suggested the potential for preferential flow. The work of Horton and Hawkins [4] was used to develop a column study to investigate the mechanisms for preferential flow within vertically layered unsaturated environments. Once the laboratory experiment was completed, numerical modelling was performed using the 2-D finite element modelling package SEEP/W [5].

## Column Study

The column study was developed and conducted at the University of Saskatchewan, Saskatchewan, Canada. The column was a 1.2 m high, rectangular, clear plastic design, with dimensions of 15 cm x 10 cm x 140 cm, (Fig. 2). Fine and coarse-grained materials were placed vertically adjacent to each other, separated by an adjustable, thin metal sheet, which ran down the center of the column. The metal sheet, or cutoff, facilitated the placement of the two materials at the beginning of the experiment and then was lowered to different elevations through the base of the column at regular intervals. The cutoff inhibited the lateral movement of water between the materials located below the height of the cutoff while the materials located above were in direct contact and free to interact [6]

Two configurations of fine and coarse-grained material were used during the column study. The first configuration consisted of fine-grained and coarse-grained sand for which the hydraulic properties had previously been determined [7] [8]. The total height of the column was 114 cm and the cutoff was adjusted throughout the experiment to heights of 79 cm, 59 cm, 39 cm, 14 cm and 4 cm. The second configuration involved a fine and coarse-grained waste rock from GSM with a total column height of 136 cm and a single cutoff height of 36 cm.

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 equal to the hydraulic conductivity multiplied by the hydraulic gradient within the soil. However, in an unsaturated soil, the hydraulic conductivity becomes a function of matric suction or degree of saturation. The flow rate through an unsaturated soil ($q_{unsat}$), under a hydraulic gradient of one, is therefore equal to the unsaturated hydraulic conductivity and can be significantly less than the saturated rate ($q_{sat}$). 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.

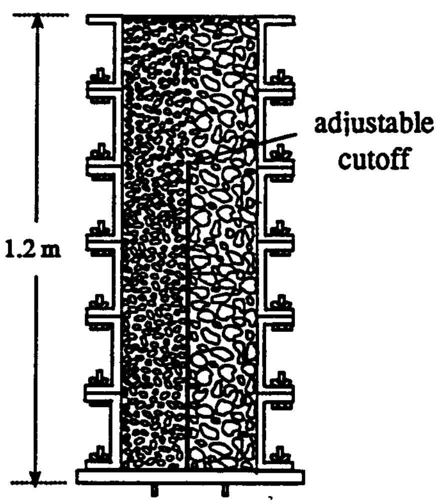


**Fig. 2** Column design [6].

A surface flux was evenly distributed over the surface of the column and separate drainage systems located at the base of the column on each side of the metal sheet allowed the discrete collection of discharge. For each cutoff height, four different surface fluxes were applied. Steady-state conditions were established and the percentage of total flow exiting from each material was recorded. Of the four applied flux rates, two were known to exceed the saturated flux rate ($q_{sat}$) of the fine-grained material and two were applied at reduced rates. Once the extent of flow partitioning had been determined for each flux rate at a particular cutoff height, the metal cutoff was lowered to allow a longer interactive length between the two materials and the four surface fluxes were reapplied.

## Results and Discussion

The unsaturated hydraulic conductivity functions for both the fine and coarse sand are shown in Fig. 3. Both of the functions presented were predicted from the measured soil-water characteristic curve and the saturated hydraulic conductivity of the material using a verified, predictive method [9]. The air-entry value for the coarse sand is less than 1 kPa. The hydraulic conductivity function for the coarse sand drops rapidly at suctions exceeding the air-entry value. The fine sand has a higher air-entry value (3 kPa) and does not drain quite as rapidly under applied suctions. The saturated hydraulic conductivity of the fine and coarse sand are $8.9 \times 10^{-4}$ cm/s and $3.0 \times 10^{-1}$ cm/s respectively. Of significance is the matric suction value of 1.4 kPa, which is where the two functions cross. At suctions less than 1.4 kPa, the coarse sand is theoretically more conductive than the fine sand. At suctions exceeding 1.4 kPa, the fine sand is more conductive than the coarse sand.

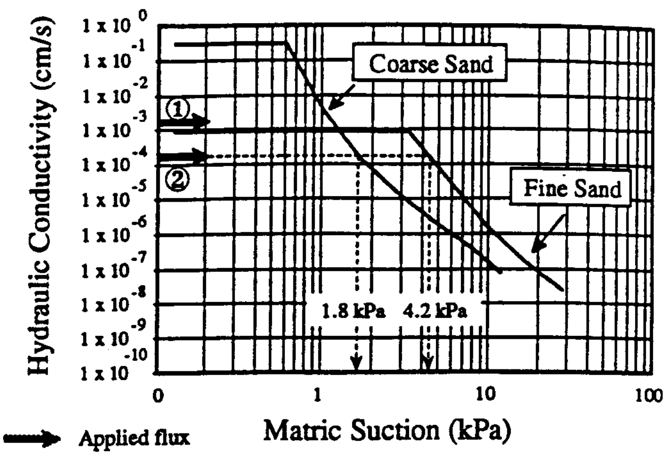


**Fig. 3** Hydraulic conductivity functions for the coarse and fine sand [6].

Arrows in Fig. 3 indicate two of the applied surface fluxes. As previously stated, under a hydraulic gradient of one, the flux rate transported through a soil is equal to the unsaturated hydraulic conductivity. The highest flux rate applied, q① = $1.33 \times 10^{-3}$ cm/s, was slightly greater than saturated hydraulic conductivity of the fine material, and the lowest flux rate applied, q② = $3.68 \times 10^{-4}$ cm/s, was less than the saturated hydraulic conductivity of the fine material.

The results of the column study for a cutoff height of 39 cm are shown in Fig. 4. When the applied surface flux, q① was greater than the saturated hydraulic conductivity of the fine material, 65% of the applied water flowed preferentially through the coarse material (Fig. 4a). The water was distributed evenly over the surface of the column, which means that 30% of the flow initially applied to the top of the fine sand flowed over to the coarse sand before a depth of 75 cm where the top of the metal cutoff was situated. Under steady-state conditions, the pore-water pressures at the surface were reduced in the fine material as the pores became water filled. The steady-state, negative pore-water pressure that developed in the coarse material was 1.2 kPa. Between matric suctions of 0 to 1.4 kPa, the coarse material was more conductive and water entering the fine material flowed preferentially toward the coarser material.

When the flux was reduced to q②, which was below the saturated hydraulic conductivity of the fine sand, the trend reversed and for the same cutoff height, 97% of the applied water flowed preferentially through the coarse material (Fig. 4b). It is apparent from the velocity vectors shown in Fig. 4b that water initially entering the coarse material was drawn over to the fine-grained material where it was transported down the length of the column. The dashed lines on Fig. 3 indicate the equilibrium suctions which attempt to establish for each material under the applied flux, q②. These steady-state suctions are 1.8 kPa in the coarse sand and 4.2 kPa in the fine sand. Within a vertically layered system where the two materials are in direct contact, the equilibrium suction which actually 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 crossover condition of 1.4 kPa and so the material that transports the majority of the water is the one exhibiting the greater conductivity, which in this case is the fine material.

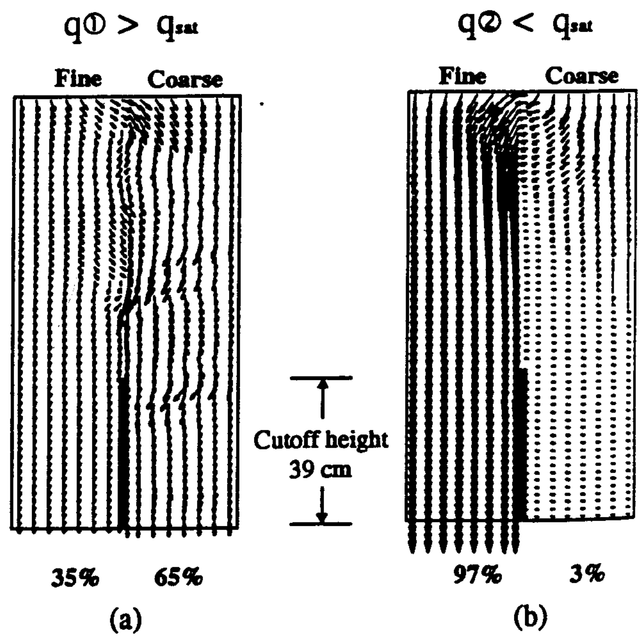


**Fig. 4** SEEP/W results for applied fluxes, q① and q②, with a 39 cm cutoff height [6].

Both laboratory and numerical modelling results showed if a longer contact length was available between the two materials, more lateral flow of water occurred with depth. For all cutoff heights, when the applied surface flux rate was greater than the saturated flux rate for the fine sand, the preferential flow occurred through the coarse sand. When the applied surface flux rate was less than the saturated flux rate for the fine sand, preferential flow occurred through the fine sand. However, similar to the Horton and Hawkins [4] column study, the results from a single test, the 3 cm cutoff height, appear to contradict this statement. Once the cutoff was lowered to a nominal height of 3 cm, virtually all of the water discharged from the bottom of the coarse layer under all applied surface flux conditions. Numerical modelling confirmed this trend but did not show as extreme a result (Fig. 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. Horton and Hawkins [4] had suggested that re-crossover occurred at the height were the coarse material became tension saturated. The pressure contours plotted in Fig. 5 highlight that the point of re-crossover 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 Fig. 3.

The column study was repeated with fine and coarse grained waste rock and one cutoff height. The results confirm that preferential flow occurs through the fine-grained material when the applied surface flux rate is less than the saturated flux rate of the fine-grained material [10].

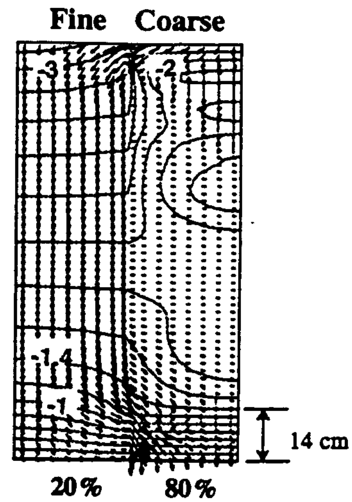


Fig. 5 SEEP/W results showing cross-over at the base of the column [6]

## 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. While there are many real-life situations where a fine and coarse-grained, vertically layered system will result in preferential flow through the coarse-grained material, it is important that the potential for the fine-grained material to transport the majority of flow is not neglected.

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