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Preferential flow in vertical layers

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Introduction

In the 1990's, the Unsaturated Soils Group at the University of Saskatchewan, in conjunction with Placer Dome Canada, undertook a research program to study the moisture flow in layered waste rock piles. A near vertical section of an end-dumped waste rock pile was exposed at the Golden Sunlight Mine in Southwest Montana, USA. Figure 1 shows a photograph of the section, which clearly shows the highly stratified nature of the dumped material. Visual inspection of the layering revealed some oxidation in the fine-grained layers, but not in the coarse layers. This suggested that moisture infiltration must have migrated to the bottom of the pile via the fine-grained layers and not so much through the coarse layers.

A laboratory testing program was undertaken by Lori Newman as part of her M.Sc. research to investigate this phenomenon. A summary of her experiments and findings are published in a paper presented at the 1997 Canadian Geotechnical Conference in Ottawa (Newman et al., 1997).

This document describes how SEEP/W can be used to model the preferential flow Newman (1997) observed in her laboratory column tests.

Figure 1. Waste rock pile at the Golden Sunlight Mine, Montana, USA.

Background

Newman (1997) constructed a clear, plastic column about 1.15 m high, with half of the column made up of fine sand and the other half of coarse sand. The column had a divider which could be retracted from the bottom once the material had been placed, as well as could be used as a seepage cut-off for various configurations. A "rain machine" was used to apply a known surface infiltration rate and the drainage was collected and measured for each side of the divided column.

The hydraulic conductivity functions for the materials used in the column are presented in Figure 2. The conductivity is present as cm/sec.

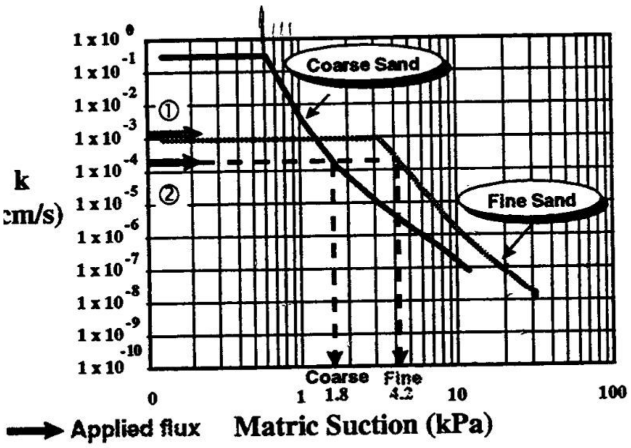

Figure 2. Hydraulic conductivity functions for the fine and coarse sand used in the column.

Newman applied two different surface flux (infiltration) rates, one less than the K_{sat} of the fine sand and one greater than the K_{sat} of the fine sand. The flow partitioning measured in the laboratory is shown in Figure 3.

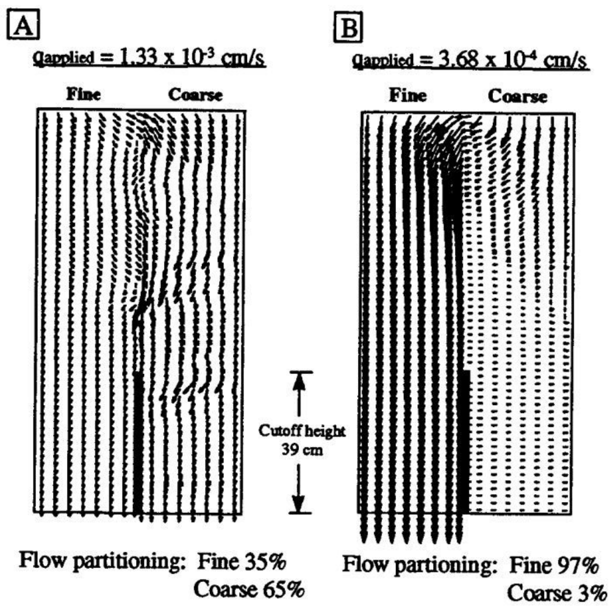

Figure 3. Flows measured in the column for two different infiltration rates.

The experiments revealed that under a lower infiltration rate, most of the flow was in the fine sand and under a higher infiltration rate, about two-thirds of the flow was through the coarse sand.

These laboratory experiments provided conclusive evidence that the flow partitioning is governed by the infiltration rate and the relative positions and shapes of the hydraulic conductivity functions for the two materials. Basically, under the low infiltration rate, the fine sand has a higher conductivity than the coarse sand, while, under the higher infiltration rate, the coarse sand has a slightly higher conductivity than the fine sand. This results from the varying suctions that develop in the two different materials under certain infiltration rates.

Numerical Simulation

The behavior observed by Newman (1997) in the laboratory can be simulated numerically with SEEP/W using the configuration shown in Figure 4. Four steady-state water transfer analyses were developed to simulate the behavior of the columns under the low and high infiltration and with or without the cut-off between the materials. The infiltration is simulated by using a specified flux rate (*q*) on the upper boundary of the column. The boundary conditions were specified as 1.3 x 10^{-5} m/sec and 3.7 x 10^{-6} m/sec for the heavy and light infiltration scenarios, respectively. The lab apparatus was constructed to ensure that small amount of suction was maintained at the base of the column. For the analyses here, the boundary condition at the base of the column is specified as -0.25 m of pressure head.

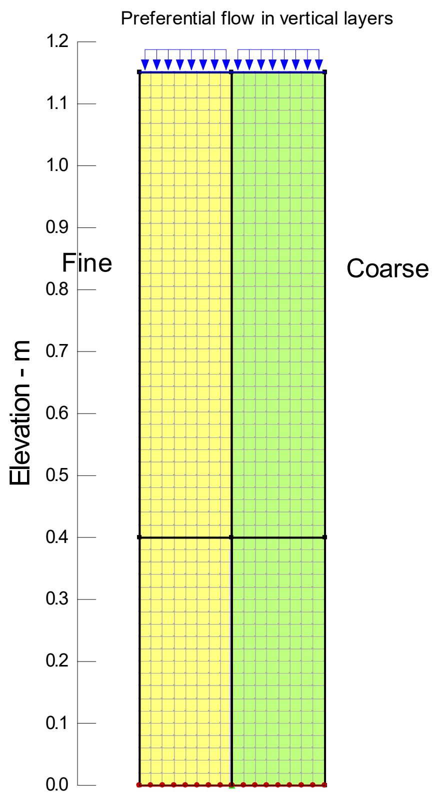

Figure 4. SEEP/W configuration for the column test simulation.

The hydraulic conductivity functions used in the SEEP/W analysis are shown in Figure 5. These functions were developed from the graphical information presented in Figure 2 and, as a result, may not be exactly the same as those used by Newman (1997). They are adequate, however, to illustrate the same water transfer processes.

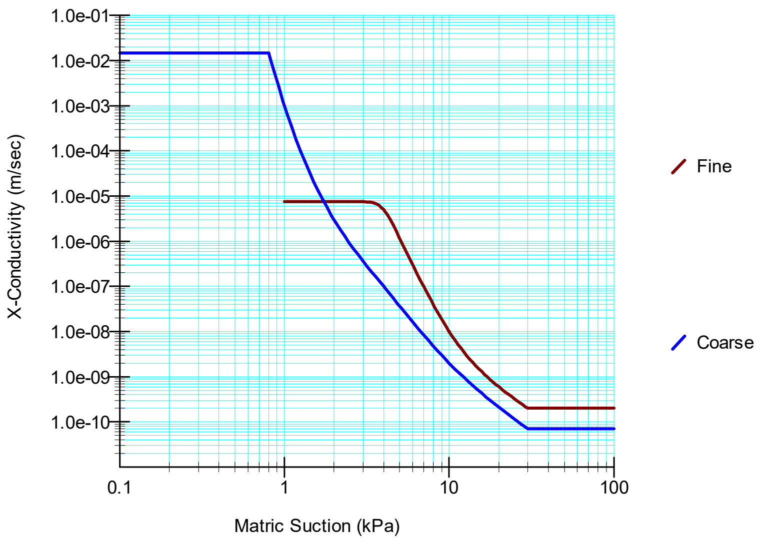

Figure 5. Hydraulic conductivity functions used in the SEEP/W analyses.

To create the cut-off in SEEP/W, interface elements with a thickness of 0.001 m were generated along the line representing the cut-off (Figure 6). The “none” material model was used to define the cut-off material and was applied to the interface elements. This would ensure that water could not flow across these elements during the simulation. A no-flow boundary condition was also applied to the node representing the cut-off at the bottom of the column.

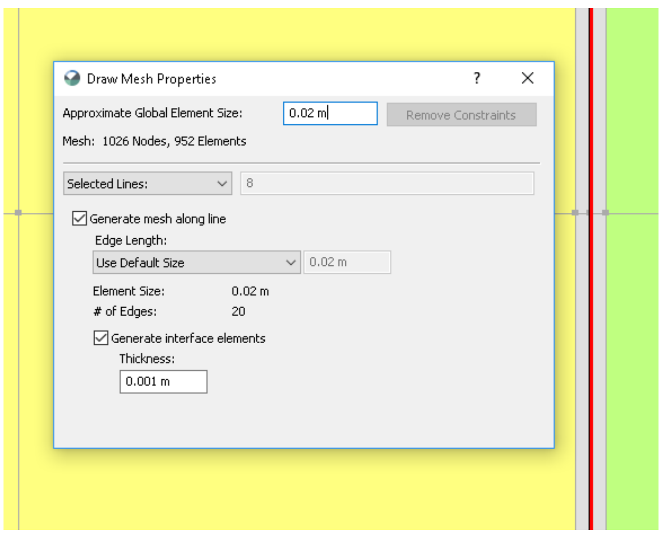

Figure 6. Interface elements active with 0.001m thickness.

Results and Discussion

The resulting total head contours, vectors, and flow paths for the light infiltration rate (3.7×10^{-6} m/sec) with the cut-off analysis are shown in Figure 7. Most noteworthy is how the water entering along the top of the coarse sand is drawn over to the left, where much of it flows down through the fine sand.

The flux partitioning is given in Table 1. The total inflow under steady-state conditions is around 1.11×10^{-6} m^3/sec. Outflow at the bottom of the column is around 93% in the fine sand and 7% in the coarse sand. These portions are very close what Newman (1997) measured in the lab, as indicated above in Figure 3, where97% was measured from the fine sand and only 3% from the coarse sand.

Table 1. Flux partitioning for the light infiltration rate with cut-off analysis.

	Total – in at top	Fine - out	Coarse - out
Rate – m³/sec	1.11×10^{-6}	1.03×10^{-6}	7.67×10^{-8}
Percentage	100	93	7

Figure 8 shows the flow partitioning when there is no cut-off present with the same light infiltration rate. In this second analysis, most of the flow is drawn over to the left and flows in the fine sand. The situation with no cut-off would be more similar to field conditions.

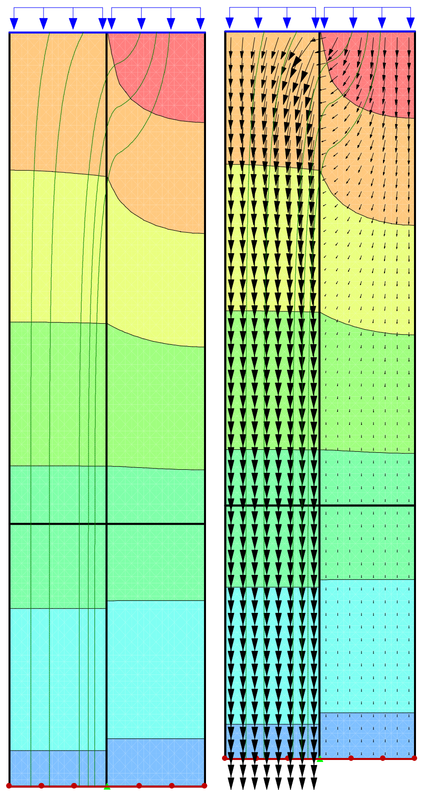

Figure 7. Flow paths and vectors for the analysis with light infiltration and the cut-off.

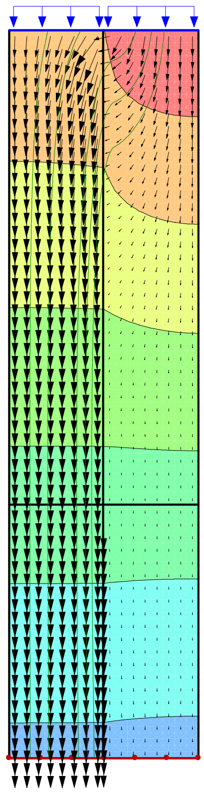

Figure 8. Flow paths and vector for the analysis with light infiltration but no cut-off.

The situation is considerably different if the infiltration rate is increased so that the conductivity of the coarse sand is slightly higher than the fine sand at the same suction. The resulting total head contours and vectors are shown in Figure 9, indicating that most of the flow is drawn into the coarse sand. With a water rate of 3.9×10^{-5} m^3/sec flowing into the column, about 65% of the flow occurs in the coarse sand (Table 2). This matches the laboratory measured value as indicated in Figure 3.

Table 2. Flux partitioning for the heavy infiltration rate with cut-off analysis.

	Total – in at top	Fine - out	Coarse - out
Rate – m3/sec	3.90×10^{-6}	1.34×10^{-6}	2.56×10^{-6}
Percentage	100	34.4	65.6

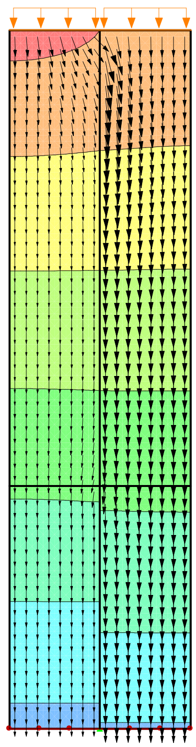

Figure 9. Flow vectors for the analysis with heavy infiltration and the cut-off.

Similar results are seen when the cut-off is not present in the analysis, with some flow being drawn back into the fine sand near the bottom of the column, prior to discharging (Figure 10).

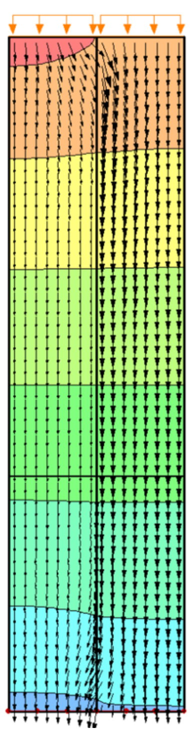

Figure 10. Flow vectors for the analysis with heavy infiltration and no cut-off.

For unsaturated flow analyses like this, it is important to ensure that the solution has converged. This can be done by making a plot of conductivity versus suction (Figure 11). The conductivity values used in the analysis and the resulting computed pore-pressure must fall on the specified conductivity function. In Figure 11, the open symbols represent the specified function and the open symbols represent the computed values. When the closed symbols fall inside the open symbols for each Gauss integration point in the mesh, the results have converged to the correct solution.

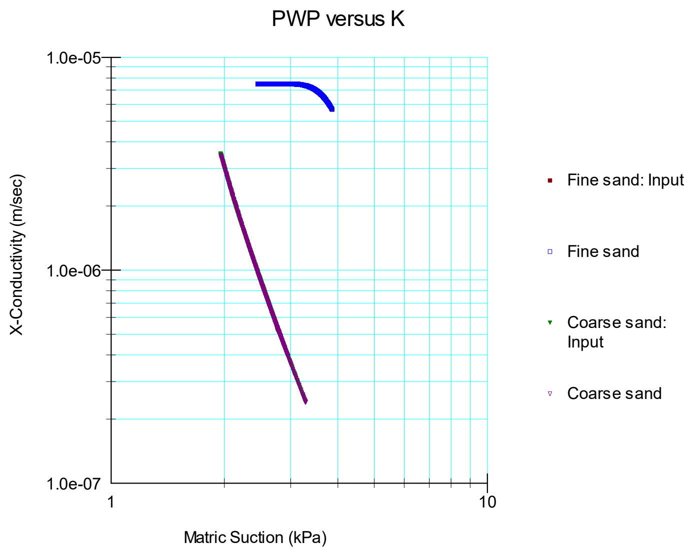

Figure 11. Matric suction versus conductivity plot to check convergence.

Summary and Conclusions

The analyses present here show that SEEP/W has the capability to numerically simulate the preferential flow that can occur in vertical and slanting granular layered systems, as observed in field conditions and in laboratory experiments. Of significance is that where the flow occurs is dependent on the infiltration rate and the positions of the hydraulic conductivity functions relative to each other.

References

Newman, L.L., Barbour, S.L. and Fredlund, D.G., (1997). *Mechanisms for Preferential Flow in Vertically Layered Unsaturated Waste Rock.* Conference Proceedings, Canadian Geotechnical Conference, Ottawa, Ontario, Canada, pp 201-208.

Newman, L.L. (1997). *Preferential Flow in Unsaturated Vertically Layered Systems.* M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.