Proceedings of the ICARD 2000, Denver, Colorado, USA, Vol. 1, pp. 257-268, May 21-24, 2000

Numerical Modeling of Vertical and Inclined Waste Rock Layers

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ABSTRACT

Conventional disposal of waste rock results in the construction of benches with fine and coarse layers dipping at the angle of repose. This interbedded structure influences flow pathways within the waste rock. A numerical modeling program was conducted to study a four-layer system consisting of alternating fine and coarse waste rock. The system was inclined from the vertical to forty-five degrees, for heights of one to twenty meters. The results show the effects of gravity as preferential flow developed under unsaturated flow conditions. The study also showed how material properties, boundary conditions, and convergence criteria affects the computed results.

INTRODUCTION

Waste rock dumps frequently contain significant quantity of reactive sulphide minerals. The piles have a high permeability and rapid drainage produces an unsaturated structure when constructed above the water table. The sulphide bearing minerals are exposed to oxidizing conditions within the atmosphere and interact with water and oxygen to produce acid rock drainage (ARD). Prevention of ARD requires that there be an understanding of the hydrogeology of the waste rock dump. Herasymuik (1996) documented detailed observations while excavating a waste rock pile at Golden Sunlight Mine (GSM) in Montana, USA. It is important to note that GSM is situated in a semi-arid climate where the potential evapotranspiration is two to three times greater than the average annual precipitation of 243 mm/yr. From these observations, Herasymuik developed a conceptual model for the hydrogeology of the waste rock pile.

The model showed that end dumped waste rock will result in stratified layers of waste rock at near residual slope and water content. The layers consist of waste rocks that have been stratified due to segregation during down slope raveling upon dumping. The stratified layers are also formed because of variations in rock type. These layers are often relatively uniform in grain size but are not continuous down the slope. The adjacent layers are also uniform but are either coarser or finer-grained. The hydraulic conductivity between adjacent layers may vary by several orders of magnitude. The different textures between the layers may be sufficient to result in preferential flow. A diagram showing the observations at GSM is presented in Figure 1.

OBJECTIVES

The results of a numerical modeling program that simulates the hydrogeology of an unsaturated end dumped waste rock pile are presented in this paper. The model considered only the flow of liquid water through the waste rock pile. Chemical reactions and gas flow are not considered.

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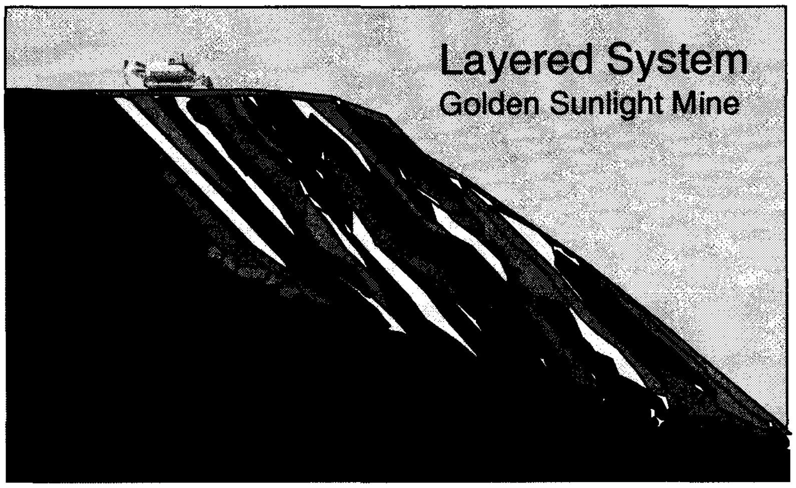

Figure 1 Diagram of layered system at Golden Sunlight Mine (Newman, 1999)

NUMERICAL MODELLING PROGRAM

Herasymuik (1996) observed that the waste rock at Golden Sunlight Mine was placed in high wedge-dump and terraced-dump configurations and were constructed by end-dumped waste rock in several lifts. The top and bottom of each lift had a fine horizontal layer associated with heavy truck traffic. In most cases, the traffic layers were observed to be near saturation. Based on these observations, a numerical model was developed for a twenty-meter lift. The model used the 2-D finite element-modeling package called SEEP/W (1995). It was initially thought that simple boundary conditions and materials properties were all that was required for an analysis. However, the model proved extremely difficult to solve. The problem was reaching convergence. Non-convergence was due to the non-linearity of the hydraulic conductivity function with respect to matric suction (i.e., negative pore-water pressures). Several variations of input parameters were used in an attempt to reach convergence. However, each variation or combination of variations did not produce a satisfactory solution. Therefore, a parametric modeling program was initiated with the simplest model based on a known solution. The flow system was systematically increased in complexity. The only known study of this nature was undertaken by Newman et al (1997) and Newman (1999). The Newman study evaluated flow through vertical coarse and fine layers of two waste rocks. The study showed that the flow pathways would vary through the coarse or fine layers depending on the flux rate. Building from the Newman (1999) study resulted in a detailed parametric study.

The first step was to establish model parameters, and then adapt the Newman (1999) study accordingly. To understand the interaction of multiple adjacent layers, four layers were used rather than two. Additional layers would increase the computational effort. Newman (1999) showed that preferential flow occurs in the fine layer during unsaturated flow. An applied flux of 10^{-5} m/s was selected and the water table was used to define the bottom boundary condition (i.e., a pressure head of zero). The overall thickness of the model was one meter with each layer a quarter of a meter thick. The model profile consisted of six flux sections. One flux section was used at the top and bottom of the model to check the water balance. The remaining four sections were used in the mid-section of the profile to measure the flux in each layer. Figure 2 shows the two-meter vertical or 90° model. The alternating fine (F) and coarse (C) layers are designated along with the flux section arrows.

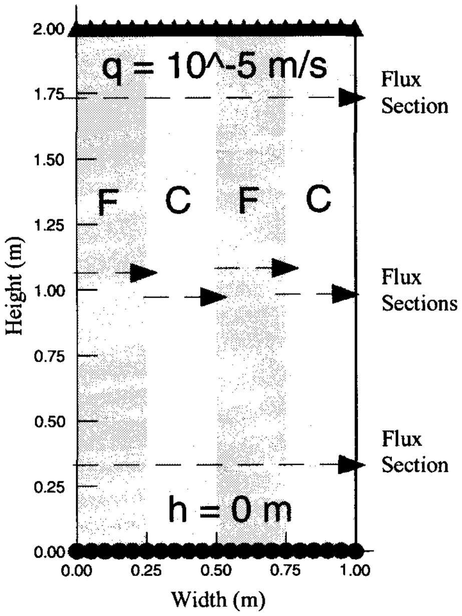

Figure 2 Two-meter vertical profile adopted for the initial model study

The materials used in the modeling study were changed from those used by Newman (1999). The fine material was changed from Beaver Creek sand to a fine rock, as described by Herasymuik (1996) for Golden Sunlight Mine. The hydraulic conductivity function for the fine layer material was obtained from the laboratory study by Herasymuik (1996). The function was computed using the Fredlund, Xing, and Huang (1994) method. The coarse layer used by Newman (1999) was also modified. The initial silica sand hydraulic conductivity function was too steep for the tall profiles. In order to solve the convergence problems, a less steep function was used for the silica sand. The hydraulic conductivity functions for both materials, and the applied flux used in the parametric study are shown in Figure 3.

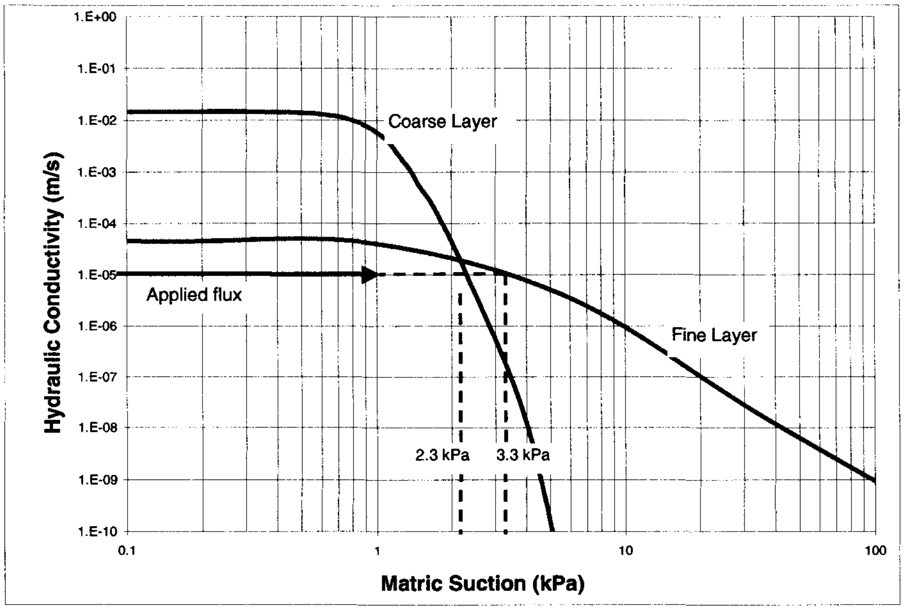

Figure 3 Hydraulic conductivity functions for coarse and fine layers

Systematic incremental changes to the initial 1.14-meter model developed by Newman (1999) were progressively implemented, to reach the targeted 20-meter sloped system for this study. The height and slope of the model was varied according to the parametric study program shown in Figure 4. First, the one-meter profile was modeled for all the slopes starting with vertical layers. Once all the slopes for a particular height were completed, the profile height was increased. Convergence was determined by two different methods for each simulation. These methods involved the use of two graphs. The first graph is provide by SEEP/W (1995) and is the vector norm versus iteration graph. As the model converges, the difference between consecutive vector norms will decrease to an acceptable tolerance. The second graph is user-generated, and uses the SEEP/W (1995) calculated hydraulic conductivities for the profile. The calculated values are then compared against the hydraulic conductivity functions of both fine and coarse materials. The calculated hydraulic conductivities should plot on or near the materials hydraulic conductivity functions to ensure that convergence has occurred. Both methods must agree to ensure complete convergence.

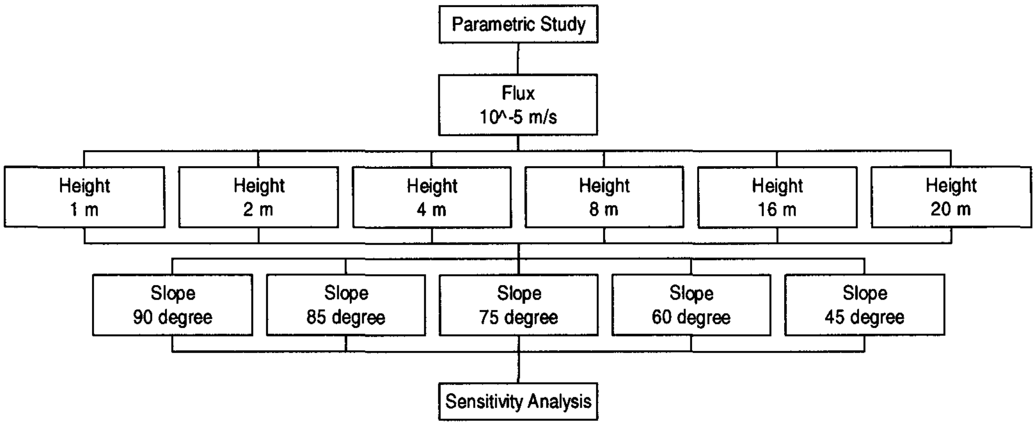

Figure 4 Parametric study program

The parametric study presented in Figure 4, shows the various conditions simulated during the study. The modeling program ran steady-state models using SEEP/W (1995) and produced solutions with convergence for 30 model simulations.

RESULTS AND DISCUSSION

Velocity vectors, pressure head contours, seepage flux across selected section, and two convergence graphs were obtain for each solution. Figure 5 shows the resulting fluxes (m/s), pressure head contours (m), and velocity vectors for the four-meter 90° and 60° models. These results are typical in appearance to the other solutions, and therefore were selected for presentation.

The resulting velocity vectors show preferential flow of the applied flux through the system. Initially the flux of 10^{-5}m/s is applied evenly across the top of the layers. Figure 3, shows where the applied flux intersects the hydraulic conductivity function for each material. The fine material will be more conductive than the coarse material for all values of matric suction greater than 2.3 kPa. The system responded by draining the flux from the coarse layers into the fine layers. Figure 5 shows that the velocity vectors do not drain evenly in sloped profile. This phenomenon can be explained by the conceptual model presented by Herasymuik (1996).

Herasymuik (1996) indicated that the water would not flow through the coarse-grained layers when the value of matric suction was greater than the value corresponding to residual water content. Rather, liquid will gather into a water droplet. When the droplet becomes sufficiently heavy, it will travel vertically. The vertical movement of water is gravity driven and depends on the slope, material properties (e.g., grain size, hydraulic conductivity), and the dimensions of the system.

The hydraulic conductivity functions for the coarse and fine layers, together with the applied flux will determine when preferential flow will occur through the fine layers. Figure 5 shows preferential flow as a crossover of flow from the coarse to the fine layers. The flow crossover stabilizes in each layer before reaching the mid-section of the profile. The flow crosses back into the coarse layers as it approaches the zero pressure head lower boundary condition. As the pressure head increases and exceeds -2.3 kPa, the coarse layers will become the preferential conduits. Hence, flow crosses back to the coarse layers before it exit the system.

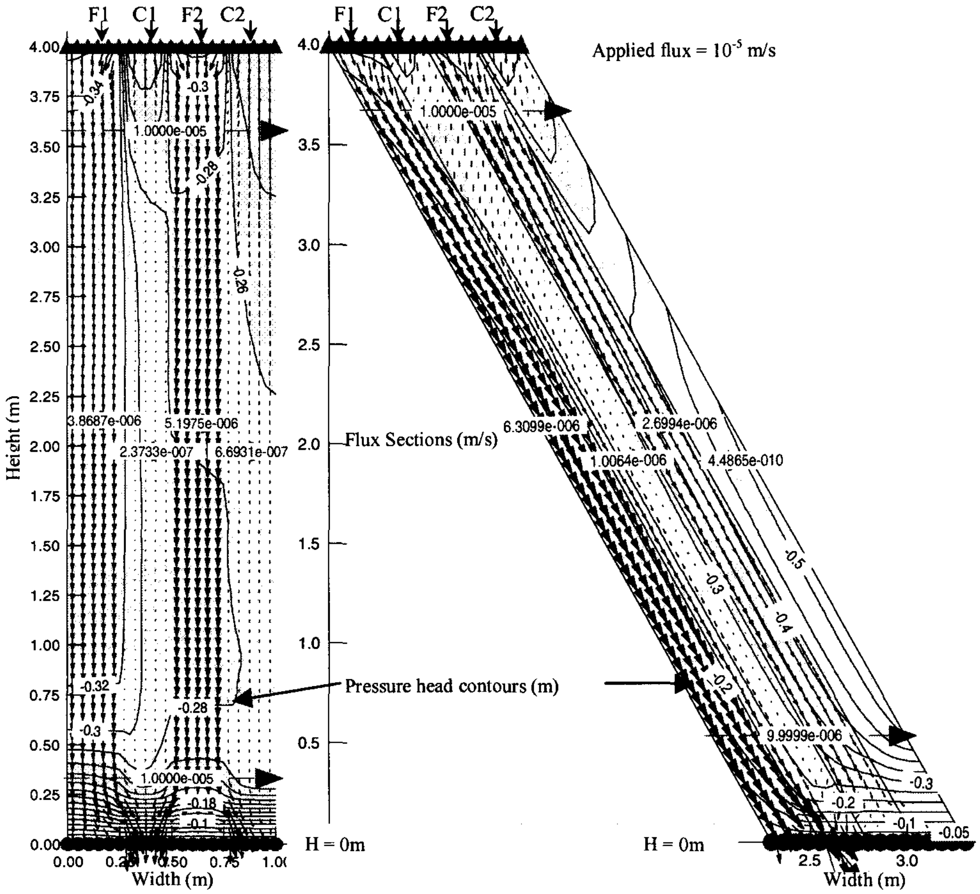

Figure 5 SEEP/W result for four-meter 90° and 60° profiles

The flux sections characterize the amount of seepage across selected cross-sections in the system. The top and bottom flux sections used to check water balance, have a negligible difference in the flux. The intermediate flux sections for the 60° model in Figure 5 shows 63%, 10%, 27%, and 0% of the total flux, in each layer, going from left to right, respectively. This corresponds to the pressure head contours. It can also be seen that the pressure heads are lowest at the top of the vertical system and decrease rapidly from left to right across the sloped systems. The low-pressure head results in the outside coarse layer producing a zone that cannot transport any of the flux.

The soil water characteristic curve (SWCC) is not required for a steady-state model. However, using the SWCC gives a measure of storage in the sloped profiles. When the first fine layer (F1) becomes saturated, the first coarse layer (C1) will stop draining into F1, and increase in degree of saturation. Therefore, if F1 is thicker, then it can store more liquid and take longer to saturate.

To better show the effects of limited storage and gravity on the flux pathway for a sloping layered system, several graphs were prepared. Figure 6 shows the fluxes passing the mid-section of the F1. The curves indicate how the amount of flux changes in the layer as the slope angle decreases from the vertical to 45° for each height.

Figure 6 shows that the flux in the layer increases consistently as the height of the system increases, regardless of the angle. The increase is proportional to the increase in contact length between the layers. There is negligible increase in flux between the 16 and 20-meter systems for all slopes. The maximum flux for each height is reached at the slope of 60°. However, the flux decreases for all heights at the 45° slope. It is difficult to explain the reason why the flux decreases for the 45° slope. If the fine layer reaches saturation, the flux would have reached a constant value similar to that for the 60° slope. One explanation is that as the system sloped to 45°, the reduction in hydraulic gradient reduced the saturated flow in the first fine layer (F1) and hence reduced vertical drainage from the adjacent first coarse layer (C1). The associated increase in pressure head enabled the coarse layer to carry more of the flux. Further study between the 60° and 45° slopes will be required to determine the angle at which the pressure heads increase sufficiently to affect the flow rates.

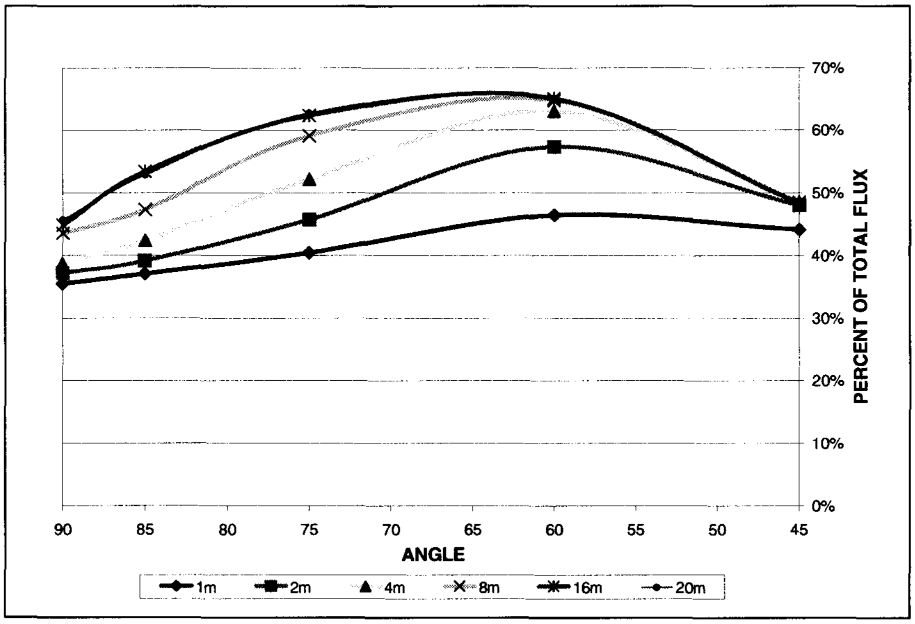

Figure 6 Changes in flux passing the first fine layer, 'F1'

Figure 7 shows the flux passing the mid-section of the first coarse layer (C1). The flux is no longer proportional to the height increase. In fact, the flux is relatively constant as the height of the system increases. However, Figure 7 shows an exponential increase in flux as the slope increases. The flux in the first coarse layer is a maximum value for the 45° slope. This is consistent with the reduction in flux in the first fine layer at 45° as shown in Figure 6. However, for all other angles both the first fine and coarse layers show an increase in flux. Therefore, the increased flux must have come from the upper layer second fine and coarse layers F2 and C2, respectively.

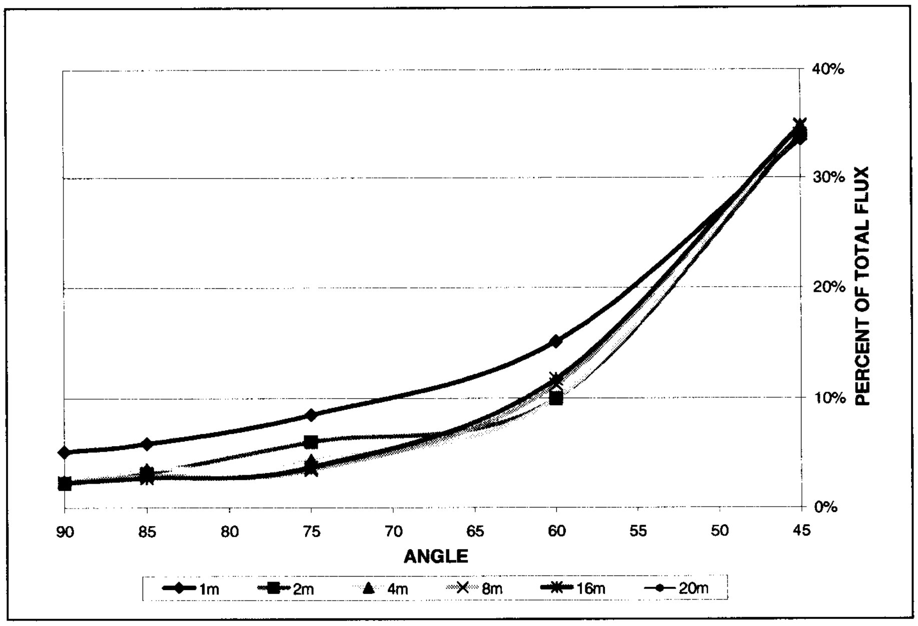

Figure 7 Changes in flux passing the first coarse layer, 'C1'

Figure 8 shows the flux passing the mid-section of the second fine layer (F2). In general, the second fine layer transmits more than half of the flux at 90°. However, as the slope angle decreases the flux steadily decreases. The proportional decrease in flux with slope angle explains the flux increase in the two lower layers.

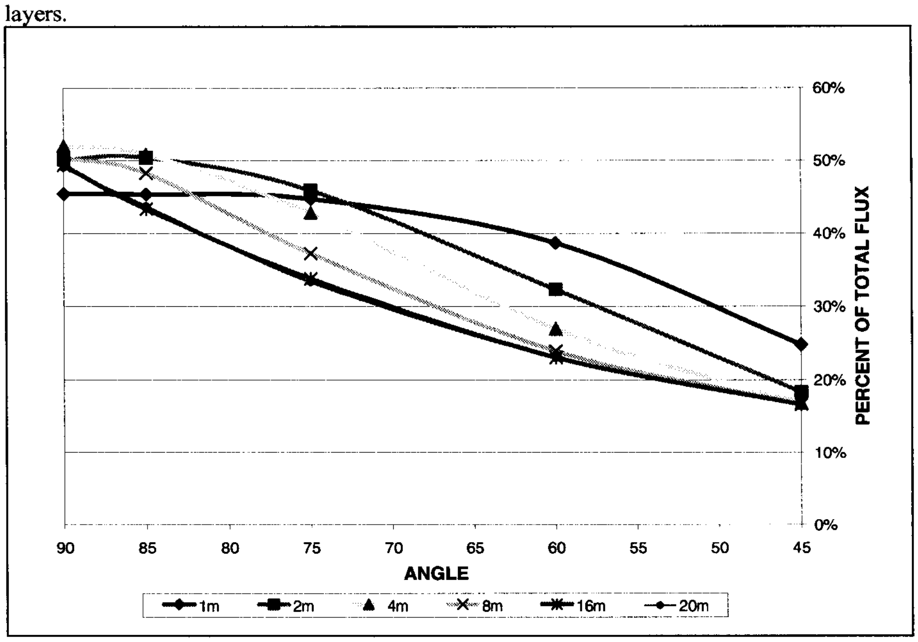

Figure 8 Changes in flux passing the second fine layer, 'F2'

Newman (1999), and Newman et al (1997) explained why the flux crosses over from the coarse layers to the fine layers. It is also important to understand how preferential flow at the top of the profile behaves with multiple layers as shown in Figure 9. For the vertical layers, the flux in C1 has two adjacent elements, which evenly contribute flux to each bordering fine layer. The second coarse layer boarders only one fine layer and drains two elements into the fine layer. This indicates that the C1 will drain twice as fast as C2. However, both C1 and C2 drain to the same flux for the 20-m profile, indicating the layers comes to equilibrium for the taller profiles (i.e., larger contact length). At the end of the initial crossover, the second fine layer transmits more flux than the first fine layer. As the slope decreases from the vertical, the flux balance moves to the lower layers as shown in Figure 10.

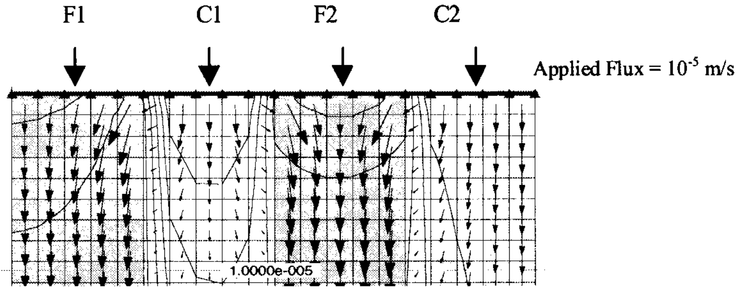

Figure 9 Top half meter of four-meter vertical solution

Figure 10 shows the overall results of the four-meter system for each slope. The figure shows the relative proportion of the flux in each layer. The log conductivity is on the secondary axis of Figure 10. The log conductivity is the log of the lowest hydraulic conductivity calculated by SEEP/W (1995) for a particular model. The trend of the log conductivity confirms that the slope angle is directly proportional to the resulting pressure heads and corresponding hydraulic conductivity. The greatest change in the log conductivity occurs at all heights between the 85° to 60° slopes. The lowest conductivity is located on the top of the coarse layers in the vertical profiles and on the mid-section of C2 in the sloped systems.

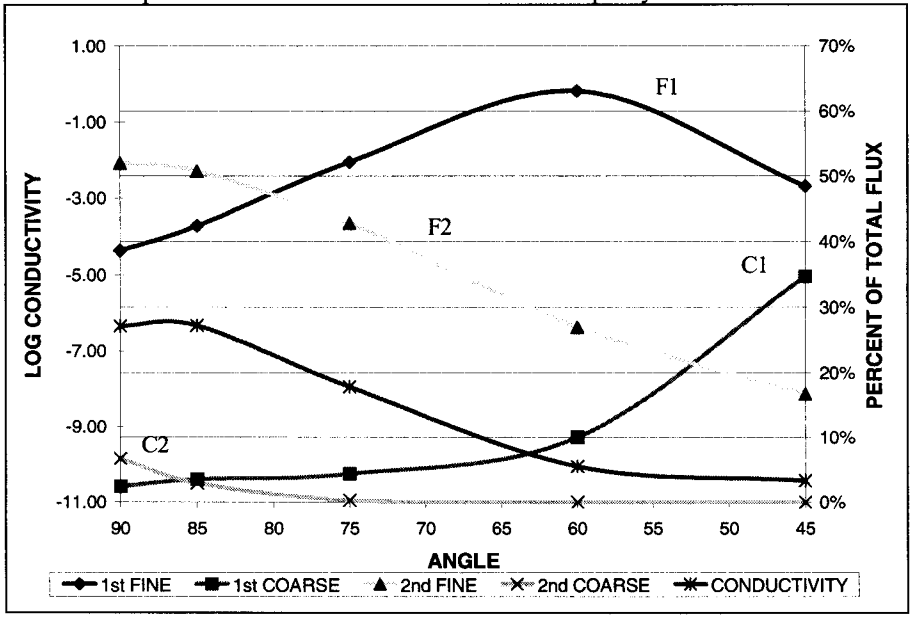

Figure 9 Flux and conductivity changes for the four-meter system

CONCLUSIONS

The results of the numerical 2-D unsaturated seepage modeling program supports the conceptual model developed by Herasymuik (1996). The numerical simulation results presented above are preliminary in nature. The results are not intended to fully describe seepage in unsaturated waste rock dumps with dipping layers of variable textures. However, the results of the analysis illustrate the trend and complexity of unsaturated flow hydrogeology in waste rock dumps. Little research has been devoted to this important area related to the prediction and analysis of seepage through waste rock dumps.

This study solves many of the problems related to using numerical modeling as a predictive design tool for describing the hydrogeology of end dumped waste rock piles. A possible application of the numerical modeling includes the design of an engineered waste rock pile in which non-reactive fine-grained material borders a reactive coarse-grained waste rock. This proposed model could simulate unsaturated flow through the fine-grain material, leaving the coarse-grain material void of significant flux. The result would be a system that can greatly reduce drainage through acid generating material.

ACKNOWLEDGMENT

The author would like to thank Professors Fredlund and Barbour for the vital assistance in completing this research. The support received from fellow graduate students, Mike O'Kane, and family was invaluable.

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