PROTOCOL FOR PRELIMINARY MODELING OF AN EVAPORATIVE COVER SYSTEM

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ABSTRACT
Preliminary numerical modeling of the soil-atmosphere interaction was conducted for a potential cover system at a proposed mining operation. Limited information was available with regard to the unsaturated soil properties such as the soil-water characteristic curve and the unsaturated permeability function of materials that might be suitable for the cover material. In order to proceed with the preliminary design, the unsaturated soil properties were estimated from grain size distribution data using estimation methodologies that have been previously proposed in the research literature. Significantly different results were obtained depending on the details of the estimation methodology and its utilization in the numerical model. It is important to obtain the most reasonable possible estimates of the unsaturated soil properties from the limited available data. In order to obtain the most accurate results possible, the modeler should use the most appropriate method for estimating the unsaturated material properties.

RÉSUMÉ
Une modélsation numérique préliminaire des interactions sol-atmosphère fut réalisée dans le cadre de la création possible d'un système de recouvrement de débrit de roche pour une opération minière. Peu d'information était disponible sur les propriétés des sols insaturés, tel que la courbe des caractéristiques sol-eau et la fonction de perméabilité des sols en milieu insaturé qui pouvait être utilisée pour les matériaux de recouvrement. Afin de procéder à la conception initiale, les propriétés des sols insaturés furent estimées en utilisant une base de données de distribution de la taille des particules et des méthodes d'estimation proposées dans la littérature scientifique. Les résultats différaient considérablement dépendament de la méthode d'estimation et de son utilisation dans le modèle numérique. Il est important d'obtenir les estimations des propriétés des sols insaturés les plus raisonnables possibles. Afin d'obtenir ces résultats, le modéliste doit utiliser la méthode d'estimation des propriétés des sols insaturés la plus appropriée.

1. INTRODUCTION

Statement of the Issue at-hand

Geotechnical engineers are often called upon to undertake a preliminary assessment regarding the suitability of an "evaporative" or "store and release" cover system for the waste rock and tailings associated with a proposed mining operation. During the preliminary stages there is generally a limited amount of soils information available upon which a design can be evaluated. The available soils data usually consists of grain size distribution curves and it is important that maximum benefit be derived from this information for preliminary design purposes.

Case History Involving a Preliminary Cover Design

The present study is based on a case history involving a preliminary design required for a waste rock pile for a proposed mine. Limited information was available regarding the soil-water characteristic curves (SWCCs) and the unsaturated permeability functions for the materials involved. There was, however, considerable grain size distribution information data available. Information was also available on the average climatic conditions in the area where the waste materials would be sited.

2. NUMERICAL MODEL FOR PRELIMINARY COVER DESIGN

Model Description

The modeling focused on three different material properties to simulate a range of potential cover materials. Each model used a one-dimensional column with a height of 40 m. A no flow boundary was set at the base of the model, and the initial head was set to 130 m below the top of the model. The height was chosen to reduce the effects of the no flow boundary on the soil-atmosphere interaction at the top of the model. The models assumed a homogeneous material throughout the height of the column, and did not differentiate between cover and waste material. The same climatic conditions were used for all the models. The three models presented in this study are 1FX, 1MC, and 2FX.

Modeling Software

Surface infiltration into the cover was simulated using a one-dimensional finite element column model using SVFlux, developed by Soilvision Systems Ltd., specifically for the analysis of seepage in saturated-unsaturated flow systems (Thode *et. al.* 2006). This software uses a solver program called FlexPDE by PDE Solutions Inc., which allows for automated mesh generation and refinement, as well as automated time step refinement.

Model Inputs

The three models used the same precipitation and evaporation conditions, and varied the cover material properties, to simulate various types of materials that could be used to construct a cover. The precipitation, evaporation, and material properties are described below.

3. CLIMATIC INPUTS FOR THE NUMERICAL MODELS

Precipitation

Precipitation data was available from a weather station at the mine site, and an average annual rainfall of 953 mm was recorded. The daily precipitation values used in the models are shown in Figure 1. The climate could be described as having a 6 month dry period from May to October and a 6 month wet period from November to April.

One part of the information required is the design precipitation intensity. The average daily precipitation was averaged over a 20 hour period for each day of rain. This was done even though the rainfall may have occurred over a relatively short period.

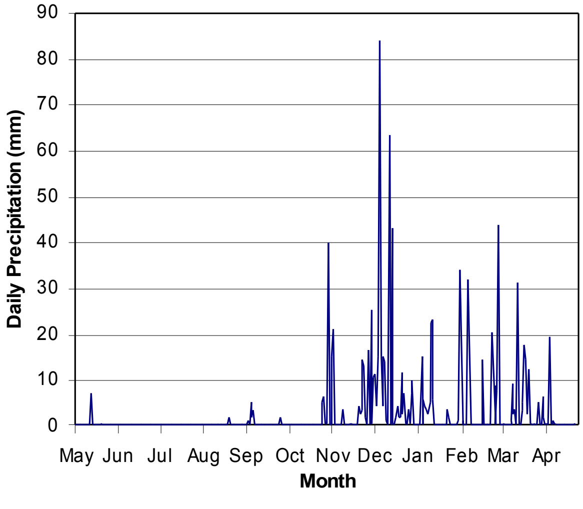

Figure 1. Daily precipitation record

Evaporation

Potential evaporation was computed based on a number of variables that characterize the climate. These variables are: i) air temperature, ii) relative humidity, iii) wind speed, and iv) net radiation. Each of the above-mentioned variables, with the exception of net radiation, was extracted from the available climatic data collected at the mine site weather station.

Figure 2 shows the daily temperature distribution for one year at the mine site. The average temperature for the months of May to October is 24.1 degrees Celsius and the average temperature for the months of November to April is 23.5 degrees Celsius. Figure 3 shows the daily relative humidity distribution for one year at the mine site. The average relative humidity during the dry season is 43.7% and the average relative humidity during the wet season is 68.4%. Figure 4 shows the daily wind speeds for one year at the mine site. Figure 5 shows the estimated daily net radiation for one year at the mine site. These were calculated based on solar radiation recorded at the site, using an albedo of 0.3 for the dry season and 0.25 for the wet season.

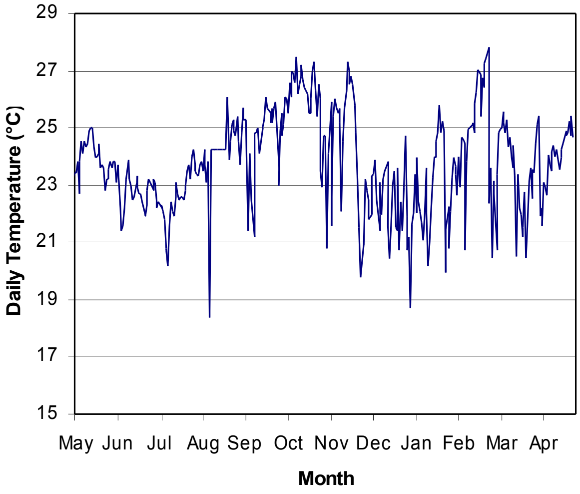

Figure 2. Daily temperature record

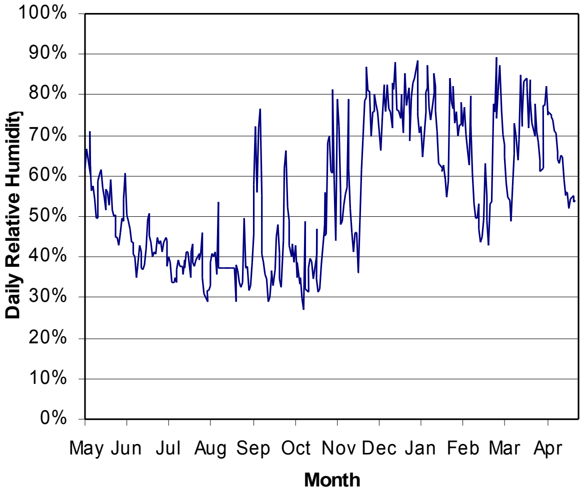

Figure 3. Daily relative humidity record

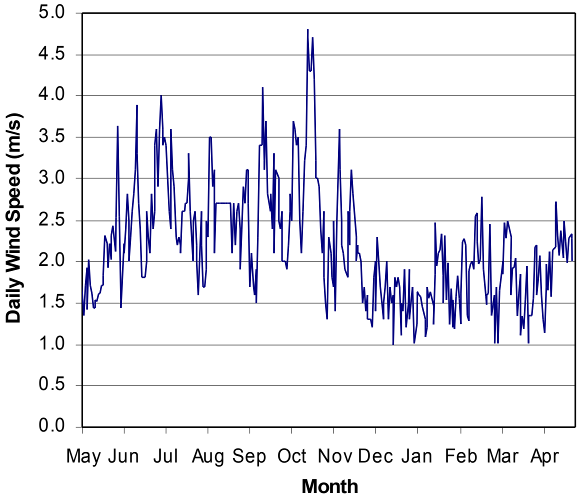

Figure 4. Daily wind speed record

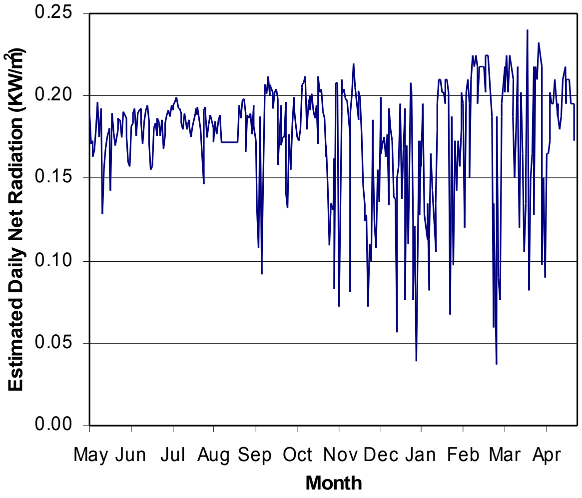

Figure 5. Estimated daily net radiation record

Potential evaporation was calculated based on the previous information using the equation presented by Penman (1948) and is shown in Figure 6.

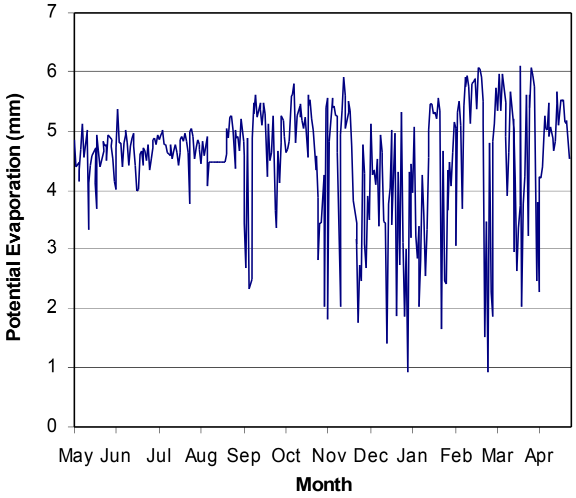

Figure 6. Potential evaporation record

4. MATERIAL PROPERTIES FOR THE NUMERICAL MODELS

The necessary unsaturated soils information required for undertaking a preliminary design of a cover system was derived primarily from the available grain size distribution data. A variety of empirical methodologies have been proposed in the research literature for the estimation of the SWCC from the grain size distribution curve, and the unsaturated permeability function from the SWCC.

Soil Properties

Material properties for models 1FX and 1MC were based on a sample of waste rock that had been passed through a 4.75 mm sieve for prior testing. The grain size distribution for this material is shown in Figure 7. Based on the Unified Soil Classification System (USCS), this material is classified as a poorly-graded gravel with sand and silt. The grain size distribution for unsaturated properties used in model 2FX is also shown in Figure 7. This material can be classified as a silt with sand.

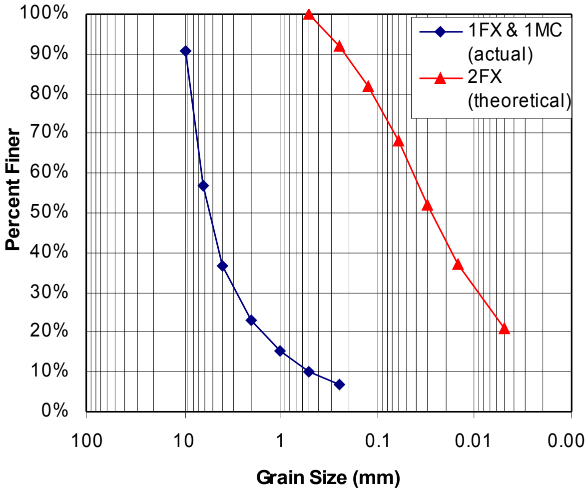

Figure 7. Grain size distributions

The same SWCC was used in models 1FX and 1MC and was estimated using the Fredlund and Wilson (1997) method, programmed in the Soilvision knowledge-based database (Fredlund 2006) from Soilvision Systems Ltd. In order to examine the effects of varying the unsaturated material properties, an additional SWCC was developed, by increasing the air entry value by approximately two orders of magnitude. An equation was fitted to each estimated SWCC using the Fredlund and Xing (1994*a*) method. Figure 8 shows the two SWCCs used in the models. Models 1FX and 1MC used the SWCC estimated from the grain size shown in Figure 7, and used an air entry value of approximately 0.1 kPa. Model 2FX used a SWCC with an air entry value of approximately 10 kPa. The corresponding grain size distribution for 2FX was back-calculated from the SWCC and is shown in Figure 7.

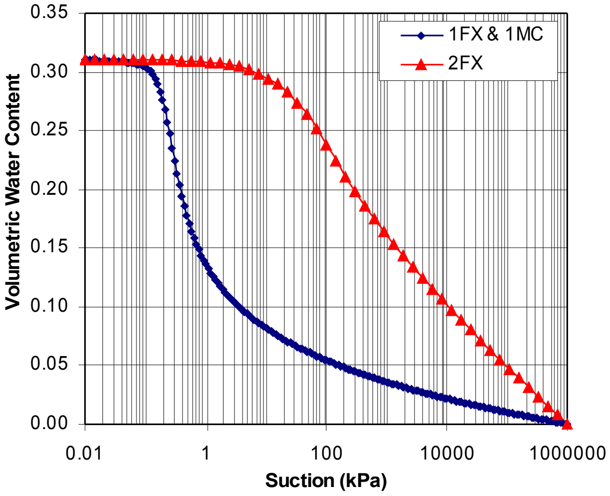

Figure 8. Soil-Water Characteristic Curves

The Fredlund and Xing (1994*b*) method was used to estimate the unsaturated permeability function for each of the SWCCs shown in Figure 8. A saturated permeability of 1.4 x 10^{-4} m/s was used to generate the unsaturated permeability functions. Models 1FX and 2FX used the actual data points generated by the Fredlund and Xing (1994*b*) method. These functions are shown in Figure 9. Model 1MC used the Modified Campbell (Fredlund 2000) unsaturated permeability function, also shown in Figure 9. The function used in model 1MC was created by attempting to use a curve fitting method to approximate the Fredlund and Xing unsaturated permeability function. The Modified Campbell method shown is often used to flatten the unsaturated permeability function to provide a more stable numerical solution.

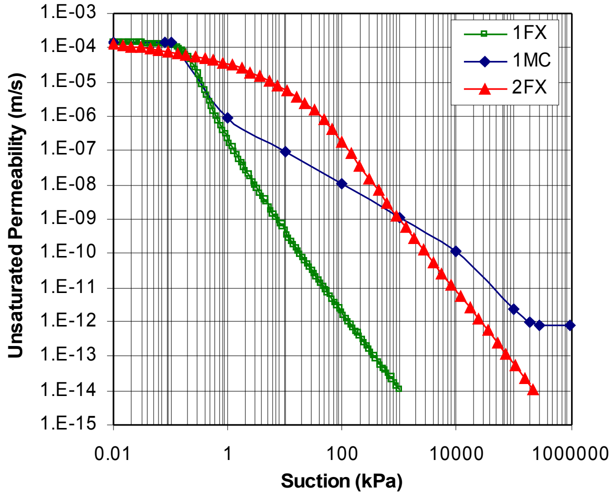

Figure 9. Unsaturated permeability functions

5. RESULTS OF THE NUMERICAL MODEL SIMULATIONS

Models were run to simulate one dry season and one wet season. The dry season extends from May to October (day 0 to day 185). The wet season extends from November to April (day 186 to day 364).

Results from model 1FX are shown in Figure 10. This figure shows the cumulative rainfall, runoff, surface flux, actual evaporation (AE), and potential evaporation (PE) for a one year period. The total cumulative flux into the model was 591 mm, indicating a net infiltration. The cumulative runoff was 1 mm.

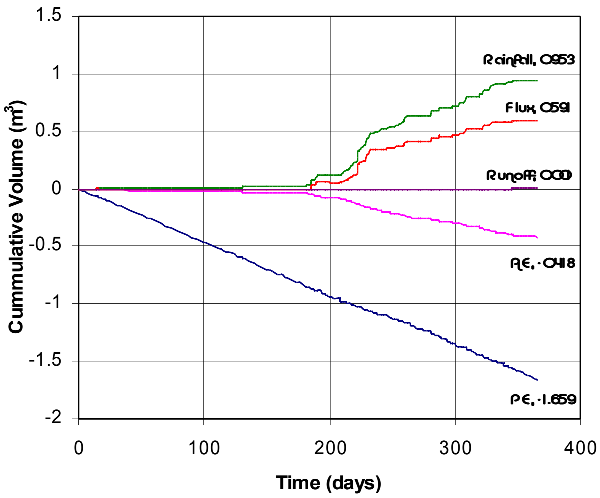

Figure 10. Cumulative flux results from model 1FX

Results from model 1MC are shown in Figure 11. The total cumulative flux was -179 mm, indicating a net evaporative condition. The cumulative runoff was 1 mm.

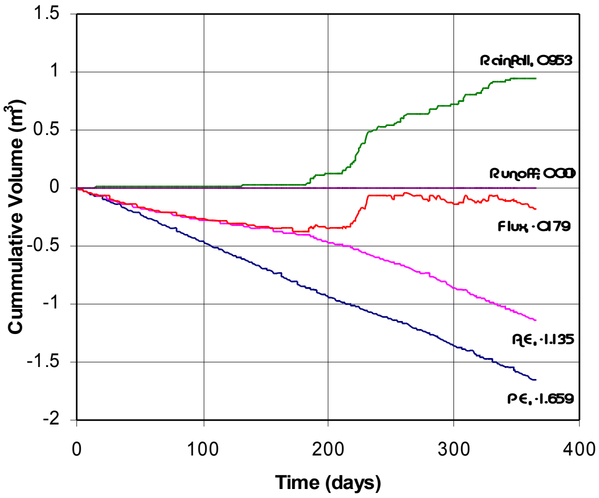

Figure 11. Cumulative flux results from model 1MC

Results from model 2FX are shown in Figure 12. The total cumulative flux into the model was -12 mm, indicating a net evaporative condition. There was negligible runoff for the model.

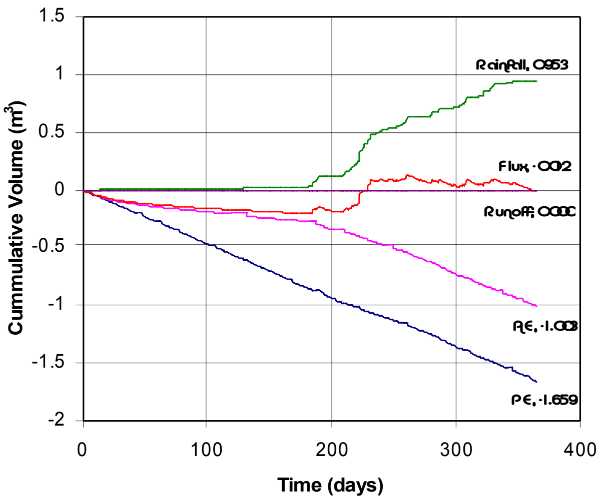

Figure 12. Cumulative flux results from model 2FX

Water content profiles for model 1FX are shown in Figures 13 and 14. Figure 13 shows water contents at depths of 0.2, 2, and 10 m, and shows the variation in water content over the one year period. The maximum water content at these depths was 7.1%. Figure 14 shows detailed water content profiles at day 150, 230, and 350, with day 150 being in the dry season, and days 230 and 350 being in the wet season. The figure indicates that most of the change in water content occurs in the upper 2 to 5 m of material, and that there is essentially no change below a depth of 10 m. The related suctions for these water contents range from approximately 1 to 1,000 kPa. The unsaturated permeability ranged from 1 x 10^{-14} to 2 x 10^{-7} m/s.

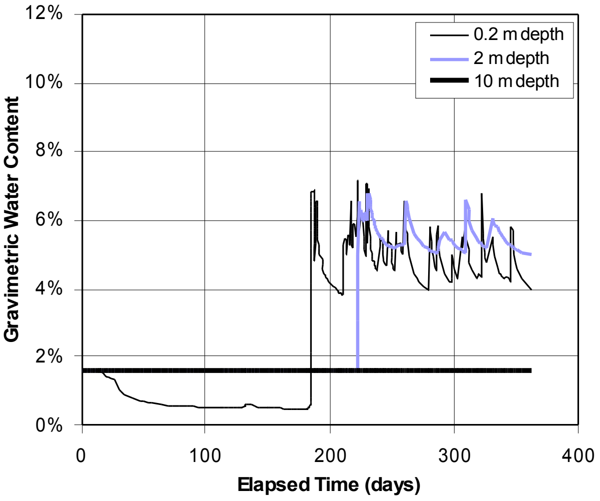

Figure 13. Water contents for model 1FX

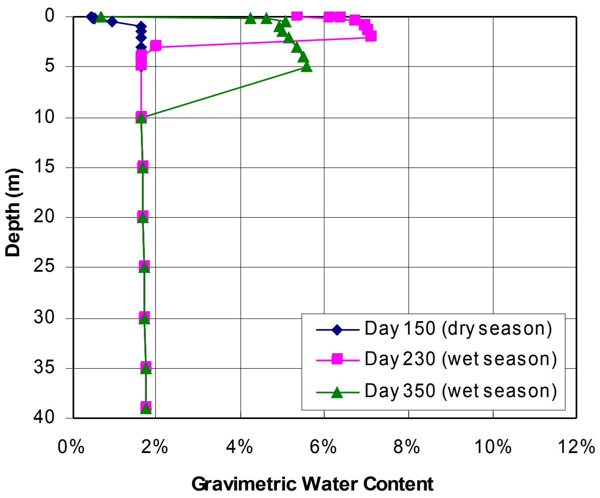

Figure 14. Water content profiles for model 1FX

Water content profiles for model 1MC are shown in Figures 15 and 16. Figure 15 shows water contents at 3 depths over one year. The figure shows little variation in water content during the dry season, while there is significant variation during the wet season, especially in the upper region. The maximum water content for the selected depths was 5.5%. Figure 16 shows detailed water content profiles at day 150, 230, and 350, and shows there to be significant change in water content within the upper 2 to 5 m. The change in water content over time is noticeable throughout the entire 40 m depth. The related suctions for these water contents range from approximately 1 to 100,000 kPa and the unsaturated permeability ranges from 1 x 10^{-2} to 1 x 10^{-6} m/s.

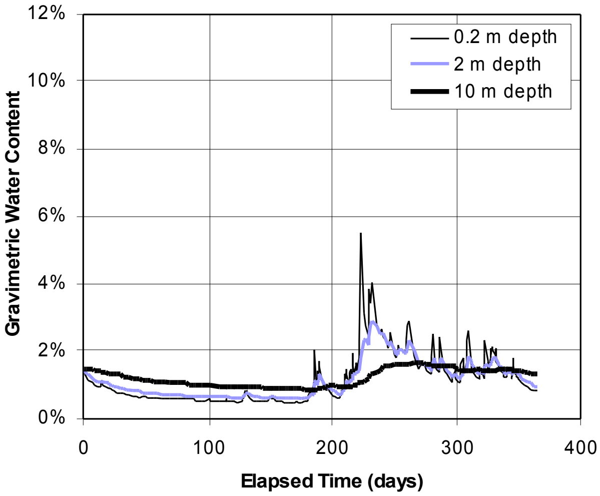

Figure 15. Water contents for model 1MC

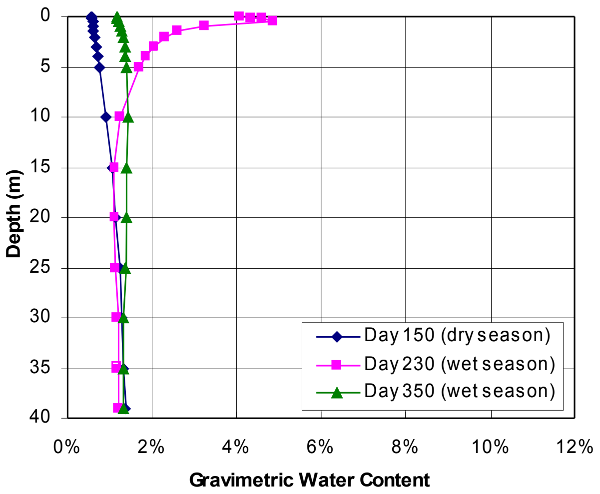

Figure 16. Water content profiles for model 1MC

Water content profiles for model 2FX are shown in Figures 17 and 18. The water contents over a one year period are shown in Figure 17, and indicate a change of -3.3% at a depth of 0.2 m during the dry season, for the initial conditions used. The higher water contents are due to the shift in the SWCC. A maximum water content of 10.4% is shown during the wet season. Figure 18 shows three water content profiles, and indicates that most of the change in water content occurs in the upper 2 to 5 m of material. The change in water content over time is noticeable to a depth of 20 m. The related suctions for these water contents range from approximately 100 to 100,000 kPa, and the unsaturated permeability ranges from 1 x 10^{-14} to 1 x 10^{-7} m/s.

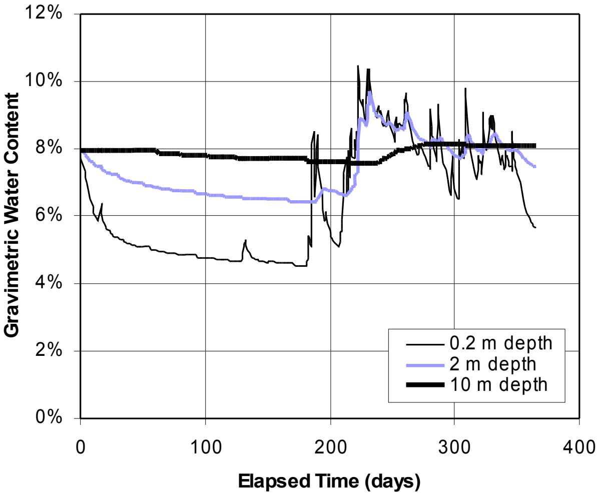

Figure 17. Water contents for model 2FX

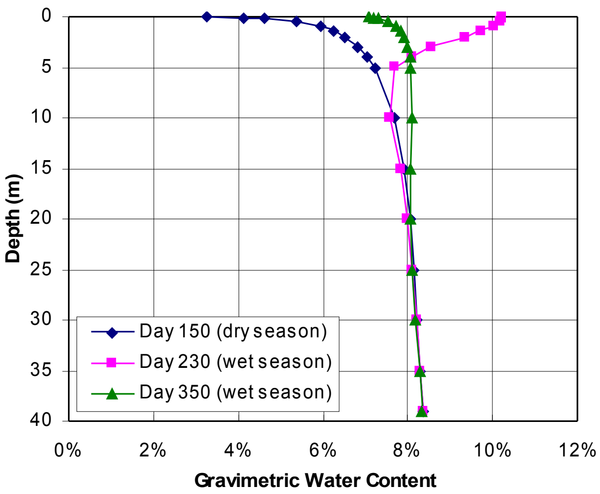

Figure 18. Water content profiles for model 2FX

6. IMPORTANCE OF THE RELATIONSHIP BETWEEN ALL UNSATURATED SOIL PROPERTY FUNCTIONS

The two primary relationships required for the numerical modeling process are the unsaturated hydraulic conductivity function and the water storage function for the possible cover materials. The study illustrates the importance of providing as strong a linkage as possible between all unsaturated soil property functions.

7. CHALLENGES OF THE PRELIMINARY MODELING EXERCISE

All of the unsaturated soil property functions are highly nonlinear in character and yield challenges to the numerical modeler and the associated computer software. The primary challenge is to ensure convergence of the solution while retaining the best estimates of all soil properties. Sometimes the modeler arbitrarily chooses a flatter unsaturated permeability function in order to obtain a more numerically stable solution. With the development of recent solvers it is now possible to use more rigorous formulations of the unsaturated permeability functions in the computer model. The study shows the importance of retaining the most accurate relationship between all unsaturated soil property functions involved in the preliminary design process.

8. DISCUSSION OF THE RESULTS OF THE NUMERICAL MODELING EXERCISE

The results of the analysis presented in this paper illustrate the potential effects of using differing interpolation methods to estimate the unsaturated permeability function for the same soil-water characteristic curve. For the climatic conditions presented, the results using the two interpolation methods varied between a net evaporation condition for model 1MC (-179 mm) to a net infiltration condition for model 1FX (591 mm).

While the unsaturated permeability function used for model 1MC (Figure 9) results in a more stable solution with a reduced solution time when compared to model 1FX, the flatter unsaturated permeability function allows moisture to be drawn back out of the model at greater depths than model 1FX, resulting in a net evaporative condition. This can be seen in Figures 14 and 16, where the changes in water content for model 1FX occurs in the upper 5 m of material, whereas there are significant changes in water content below 5 m in model 1MC.

The evaporative flux and actual evaporation for model 1MC are somewhat similar to those for model 2FX. The unsaturated permeability function used in model 1MC was estimated using the Modified Campbell (Fredlund 2000) method, and the function for model 2FX was estimated using the Fredlund and Xing (1994*b*) method. The material used in model 1MC can be described as a poorly-graded gravel with silt and sand, and the material used in model 2FX can be described as a silt with sand. Figure 7 illustrates the contrast in material gradation between the two materials. In contrast, when the Fredlund and Xing (1994*b*) method is used, as in model 2FX, the two material gradations result in contrasting results and emphasize the importance of using a rigorous methodology when computing the unsaturated properties.

Failure to maintain the most accurate assessment of the unsaturated soil property functions can result in widely diverging computer results. Accurate characterization of the unsaturated soil properties is one of the key factors in designing a cover system (Fredlund and Wilson, 2006). The study involved a parametric type analysis that illustrated the widely divergent cover designs that could be arrived at simply by changing the unsaturated soil property functions.

9. CONCLUSIONS OF THE STUDY

The study emphasizes the necessity for using the most accurate and scientifically defensible methodologies for estimating the unsaturated material properties. For this study, the authors judged the Fredlund and Xing (1994b) method for estimating the permeability function to be the most accurate. The model results predicted a range of 0% to 62% infiltration of the annual precipitation depending on which of two permeability function estimation methods was used. With recent advances in solver technology and computer speed, the need to adjust the unsaturated permeability function to increase numerical stability is generally no longer necessary.

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