Unsaturated Seepage Modeling Made Easy

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Introduction

Fresh out of university, one of the first challenges I was presented with was a seepage modeling problem. My employer had, of course, purchased thousands of dollars of seepage modeling software and it was my responsibility to recover the cost of this software by demonstrating it's worth. I had experience in both seepage modeling as well as the programming of finite element seepage software so I eagerly pursued the problem at hand. The problem involved transient flow of water in both the saturated and unsaturated zones of a soil profile and, as such, required two soil functions for each soil. A soil-water characteristic curve, (SWCC), and a hydraulic conductivity curve were required as input into the finite element seepage program. Two soil types were involved in the problem and I approached my employer for the four required soil property functions. I naturally expected these functions would be provided as they consistently were in university.

I then learned what most graduates learn when attempting to do seepage modeling. At $3000 to $5000 per test, there was little or no money in the budget to experimentally determine these soil functions. A search for typical ways to estimate these soil functions similarly came up dry. In the end, a rough, hand-drawn, “estimate” of these soil functions was used and the analysis proceeded. Several thousand dollars of state-of-the-art seepage analysis software was limited by the lack of information.

Role of the Soil-Water Characteristic Curve

The soil-water characteristic curve (i.e., relationship between water content and suction) has become of great value in estimating unsaturated soil property functions. The characterization of seepage, for example, in terms of a hydraulic head gradient and a coefficient of permeability function appears to be generally accepted (Fredlund, 1995). Figure 1 illustrates the relationship between the soil-water characteristic curve and the coefficient of permeability function for the unsaturated portion of the soil profile. The use of nonlinear soil property functions for analyzing unsaturated soils problems appears to be gaining general acceptance. This article primarily addresses indirect procedures that can be used to estimate unsaturated soil property functions for use in the numerical modeling of saturated/ unsaturated soil systems in engineering practice.

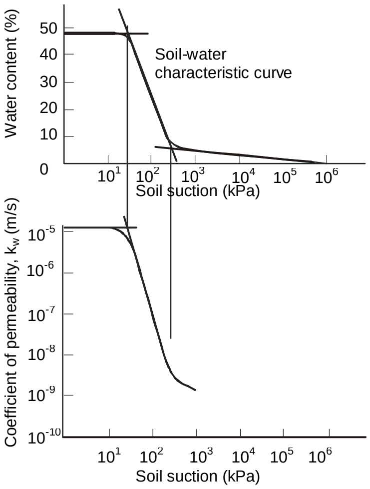

Figure 1. Visualization of the relationship between the coefficient of permeability function and the soil-water characteristic curve.

Properties of the Soil-Water Characteristic Curve

The behavior of unsaturated soils (i.e., unsaturated soil property functions) are strongly related to the pore size geometry and the pore size distribution. The soil-water characteristic curve becomes a dominant relationship for understanding unsaturated soil behavior. The soil-water characteristic curve defines the degree of saturation corresponding to a particular suction in the soil and becomes a measure of the pore size distribution of the soil. Figure 2 shows the general features of the desorption and adsorption branches of a soil-water characteristic curve. An equation proposed by Fredlund and Xing (1994) to empirically best-fit the soil-water characteristic curve is as follows:

$$\theta_w = C(u_a - u_w)\frac{\theta_s}{\left\{\ln\left[e + \left((u_a - u_w)/a_f\right)^{n_f}\right]\right\}^{m_f}} \qquad \textbf{[1]}$$

where: θ_w = volumetric water content, θ_s = volumetric water content at saturation, e = 2.718….…, (u_a - u_w) = soil suction, a_f = soil parameter related to the air entry of the soil and equal to the inflection point on the curve, n_f = soil parameter related to the rate of desaturation, m_f = soil parameter related to residual water content conditions, $C(u_a - u_w)$ = correction factor to ensure that the function goes through 1,000,000 kPa of suction at zero water content.

The soil-water characteristic curve can be used to compute approximate soil property functions for unsaturated soils. Examples are the coefficient of permeability function, the coefficient of water volume change function and the shear strength function (Fredlund, 1995). While it is relatively easy to measure the soil-water characteristic curve in the laboratory, it is still quite costly and the test has not found its way into most conventional soils laboratories. For this reason, estimation of the soil-water characteristic using grain size distribution and volume-mass properties is beneficial.

Approaches to Obtain Unsaturated Soil Property Functions

At the start of my graduate studies I set out with the intent of solving the problem of coupled seepage and volume change for unsaturated soils. I soon discovered that the most difficult part of solving coupled problems in unsaturated soils was not solving the coupled equations but rather obtaining input that is reasonable and physically realistic. I noticed that most of the problems with non-convergence and instability in finite element software were due to unreasonable input.

This realization led to the development of a theoretical framework which outlines proposed methods for working with unsaturated soil properties and functions. The framework was later developed into a software knowledge-based database system called SoilVision^{TM}. The primary purpose of the software is to provide the scientific community with a large database of unsaturated soils information as well as theoretical methods of estimating the behavior of unsaturated soils. The system will then allow unsaturated soil analysis where data is limited. The software allows the following methods to be implemented.

Several approaches can be taken towards the determination of unsaturated soil property functions (Fig. 3). The term, **unsaturated soil property functions,** refers to such relationships as: 1.) coefficient of permeability versus soil suction, 2.) water storage variable versus soil suction, and 3.) shear strength versus soil suction. Laboratory tests can be used as a direct measure of the required unsaturated soil property. For example, a (modified) direct shear test can be used to measure the relationship between matric suction and shear strength. These tests can be costly and the necessary equipment may not be available. Therefore, it may be sufficient to revert to an indirect laboratory test involving the measurement of the soil-water characteristic curve for the soil. The soil-water characteristic curve can then be used in conjunction with the saturated shear strength properties of the soil, to predict the relationship between shear strength and matric suction. Some accuracy will likely be lost in reverting to this approach; however, the trade-off between accuracy and cost may be acceptable for many engineering projects.

Figure 3 also shows the possibility of using a classification test for the prediction of the desired unsaturated soil property function. A classification test such as a grain size analysis is used to estimate the soil-water characteristic curve which in turn is used to determine the unsaturated soil property function. A theoretical curve could be fitted through the data from a grain size analysis (Fig. 4). The theoretical grain size curve is then used for predicting the soil-water characteristic curve. A comparison of the estimated soil-water characteristic curve with experimental data is shown in Fig. 5. While there may be a further reduction in the accuracy of the estimated unsaturated soil property function, the engineer must assess whether or not the approximated soil function is satisfactory for the analyses which must be performed.

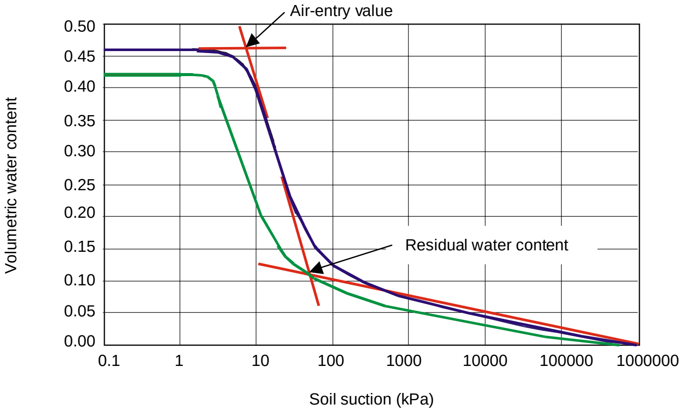

Figure 2 Definition of variables associated with the soil-water characteristic curve

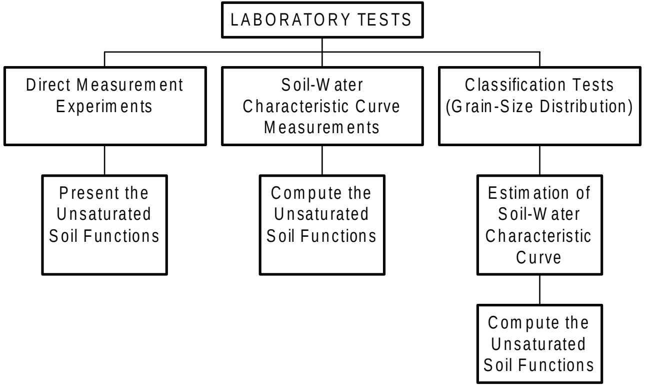

Figure 3 Approaches that can be used in the laboratory to determine the unsaturated soil properties.

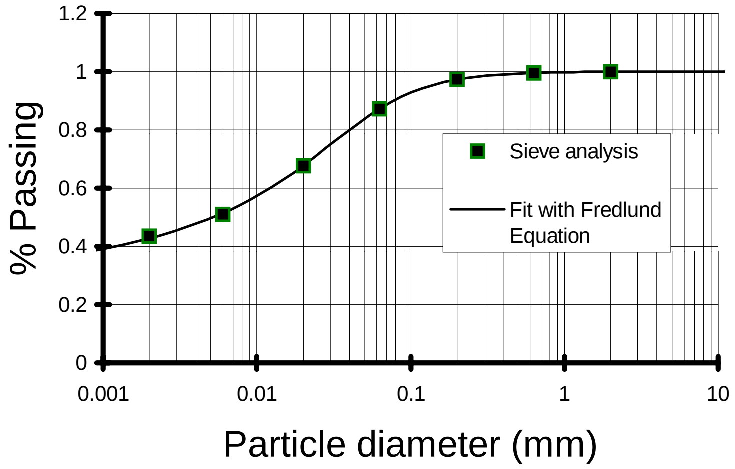

*Figure 4 Grain-size distribution curve fit for a Silty Clay (#10838***).**

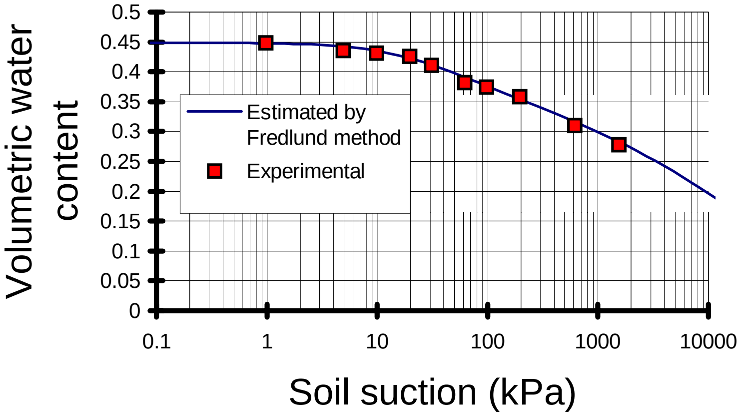

Figure 5 Comparison between experimental and estimated soil-water characteristic curves for Silty Clay (#10838

Figure 6 illustrates how one of several approaches can be used to determine the unsaturated soil property functions when using the classification and/or soil-water characteristic curve in conjunction with a knowledge-based system, to compute the unsaturated soil property functions. Plausible procedures can best be viewed within the context of a database of soil-water characteristic curve information and a knowledge-based system. Ongoing use is made of data accumulated from other laboratory studies. The first suggested procedure involves matching measured soil-water characteristic curves with soil-water characteristic curves already in the database. The measured soil-water characteristic curves can be either used to compute unsaturated soil property functions or can be used to select unsaturated soil property functions already in the database.

The second suggested procedure involves matching measured classification properties (i.e., grain size curves) with classification properties already in the database. Once one or more similar soils have been found, corresponding soil-water characteristic curves can be retrieved from the database. These soil-water characteristic curves data can be used to compute suitable unsaturated soil property functions or existing unsaturated soil property functions can be retrieved from the database.

The third suggested procedure involves working directly with the measured grain-size distribution curve. There may also be some value in comparing the grain size curve to grain size curves in the database. Soil-water characteristic curves can then be computed and compared to soil-water characteristic curves in the database. A decision must be made regarding a reasonable soil-water characteristic curve and then the unsaturated soil property functions can be computed. Each of the above suggested procedures becomes increasingly less precise.

The advantages to this approach are numerous.

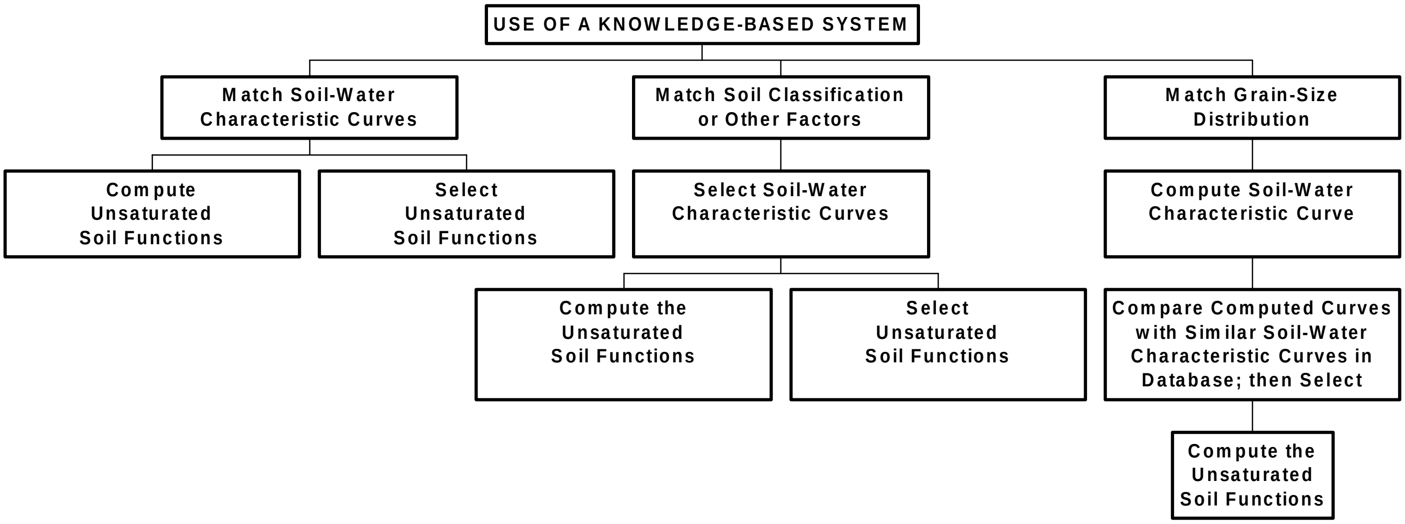

Figure 6 Approaches that can be used to determine the unsaturated soil property functions when using classification tests and a data base.

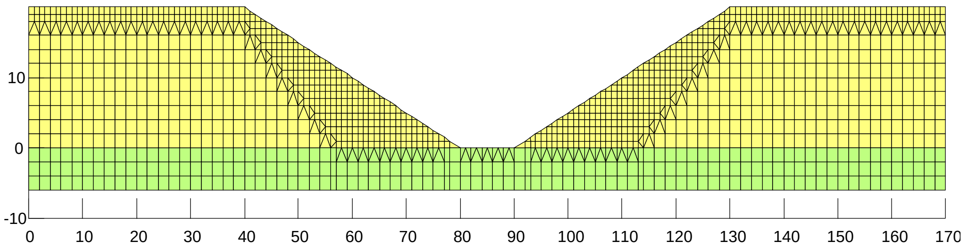

Figure 7 Problem definition for site in Papua New Guinea.

Firstly, an estimate of the unsaturated behavior of a certain soil is quickly available. Unsaturated soil mechanics has often been avoided due to complexity. The SoilVision system alleviates this complexity. Secondly, the cost of estimation of soil behavior is greatly reduced. Testing of unsaturated soil property functions can cost thousands of dollars. SoilVision provides estimates without the high cost of experimental testing. Thirdly, SoilVision makes the estimation of behavior of unsaturated soils easy so that inexperienced professionals can work in this difficult area.

An Example of an Environmental Application

An example application of this technology is the modeling of water seepage through mine tailings. A mine site in Papua, New Guinea is presented in this example. A eroded drainage ditch through mining tailings over a clay layer forms the problem (Figure 7). Two types of analysis are required; steady state and transient state. A simulated rainfall of 5.3 meters per year is simulated in the steady state analysis. A high rainfall is chosen to simulate the wet climate found in Papua New Guinea. The purpose of the steady state analysis is to determine the location of the water table. The water content of the shoulders of the drainage ditch under steady state is unknown. Finite element seepage analysis will be performed to determine the water content throughout the drainage ditch under steady state conditions.

A drought is simulated in the transient analysis to analyze how long it would take to fully desaturate the tailings. The results from the steady state analysis will be used as a starting point for the transient analysis. An evaporation rate of 1.0 meter per year is placed as a flux on top of the tailings. The information given is the volume-mass properties and grain-size distributions for both the mining tailings and the underlying clay layer. From the given information it is necessary to estimate a soil-water characteristic curve and hydraulic conductivity curve for both the clay and the mining tailings in order to perform an adequate seepage analysis.

Soil Properties

Volume-mass properties of void ratio = 0.80, saturation = 98%, and specific gravity = 2.66 were given for the mine tailings. A grain-size distribution as shown in Figure 8 was also given for the mine tailings. The clay underlying the mine tailings had given volume-mass properties dry density = 1430 kg/m^3 saturation = 100%, and specific gravity = 2.65. A grain-size distribution was also given for the underlying clay and can be seen in Figure 9. The mentioned information formed the basis for the required analysis.

Input into SoilVision

The first task at hand is to input the given information into SoilVision. Volume-mass, geography, and a description of the soil are entered into the database system. A typical page from the database can be seen in Figure 10. Secondly, the grain-size information must be input and fit with an equation. The final fit can then be seen in Figure 8.

Once the grain-size distribution is entered, the soil must be classified. Classification is necessary for SoilVision's Rule Base to properly extract similar soils from the database. Classification by the USDA method classifies the mining tailings as a **SAND**.

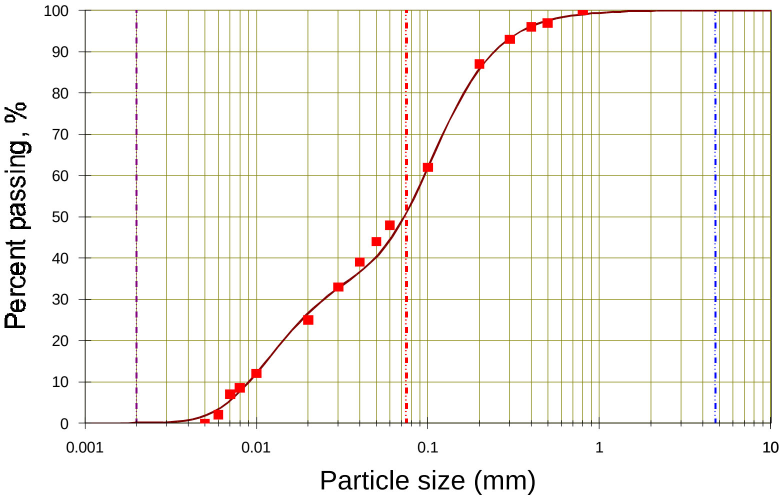

Figure 8 Given grain-size distribution for the mine tailings #11505.

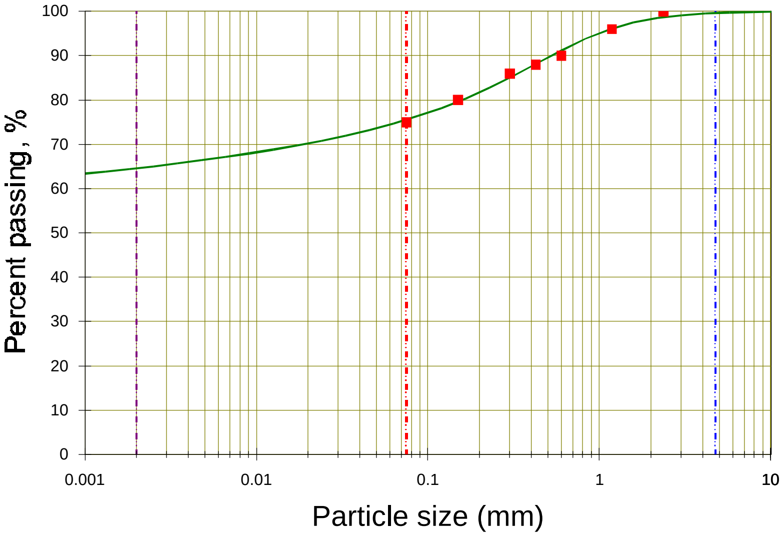

Figure 9 Given grain-size distribution for underlying clay #11638.

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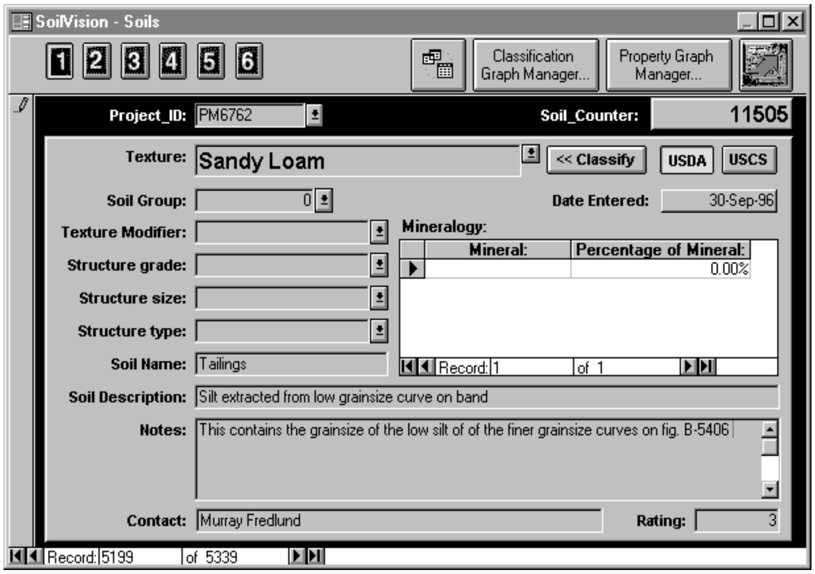

Project_ID: PM6762

Soil_Counter: 11505

Texture: Sandy Loam

Soil Group: 0

Date Entered: 30-Sep-96

Texture Modifier:

Structure grade:

Structure size:

Structure type:

Mineralogy:

Mineral:	Percentage of Mineral:
	0.00%

Record: 1 of 1

Soil Name: Tailings

Soil Description: Silt extracted from low grainsize curve on band

Notes: This contains the grainsize of the low silt of of the finer grainsize curves on fig. B-5406

Contact: Murray Fredlund

Rating: 3

Record: 5199 of 5339

Figure 10 Sample input form for soils information.

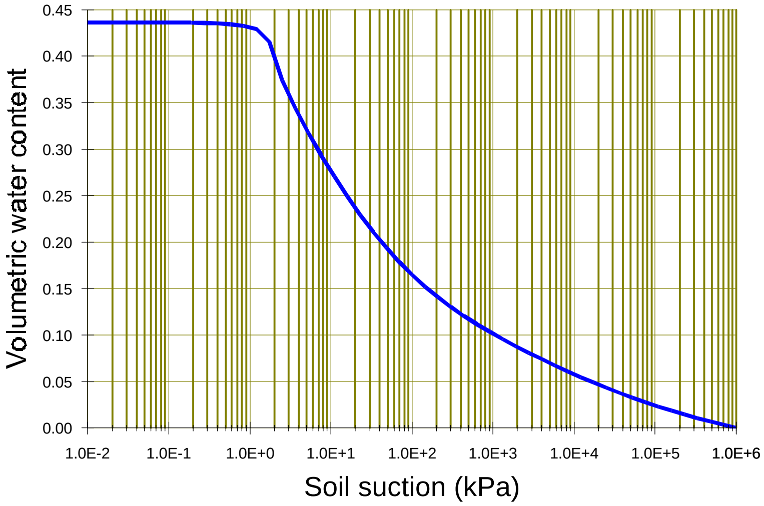

Figure 11 Soil-water characteristic curve estimated by the Fredlund and Wilson method (1997) for mine tailings #11505.

The soil-water characteristic curve must now be estimated. An accurate way of estimating the soil-water characteristic curve is by the Fredlund et al. (1997) method provided within SoilVision. The algorithm estimates the soil-water characteristic curve from volume-mass properties and the grain-size distribution of a soil. A packing porosity was chosen for the mine tailings and this produced a soil-water characteristic curve as shown in Figure 11.

A graph of the estimated soil-water characteristic curve can be seen in Figure 11. If some uncertainty exists regarding the prediction, the estimated results can be compared to experimental results in the database by querying the database and graphing groups of experimentally measured soil-water characteristic curves. An example of this is shown in Figure 12. The database was queried for soils with similar grain-size distributions. The corresponding experimentally measured soil-water characteristic curves were plotted along with the estimation in Figure 13. The database contains over 600 soils with matching experimentally measured grain-size distributions and soil-water characteristic curves. The knowledge-based system not only provides the user with an estimate of the soil-water characteristic curve but also provides an indication for the possible variance in a certain situation.

Estimating the Hydraulic Properties of Soil

It is now necessary to estimate the hydraulic conductivity of the tailings and the clay. The most variable parameter of a soil is its saturated hydraulic conductivity. SoilVision provides several ways of estimating this parameter because of this variation. Hazen's equation, the Kozeny-Carmen equation, and experimental values from the database are three ways that have been implemented in SoilVision to determine the saturated hydraulic conductivity of a soil. Saturated values of hydraulic conductivity for the mine tailings and the underlying clay were experimentally tested. A saturated hydraulic conductivity of 1.1 x 10^{-5} m/s was used for the mine tailings and a value of 8 x 10^{-9} m/s was used for the underlying clay. Once the saturated hydraulic conductivity is estimated,. the entire hydraulic conductivity curve can be estimated based on the soil-water characteristic curve and the saturated hydraulic conductivity. A graph of the final equation can then be viewed in Figure 14.

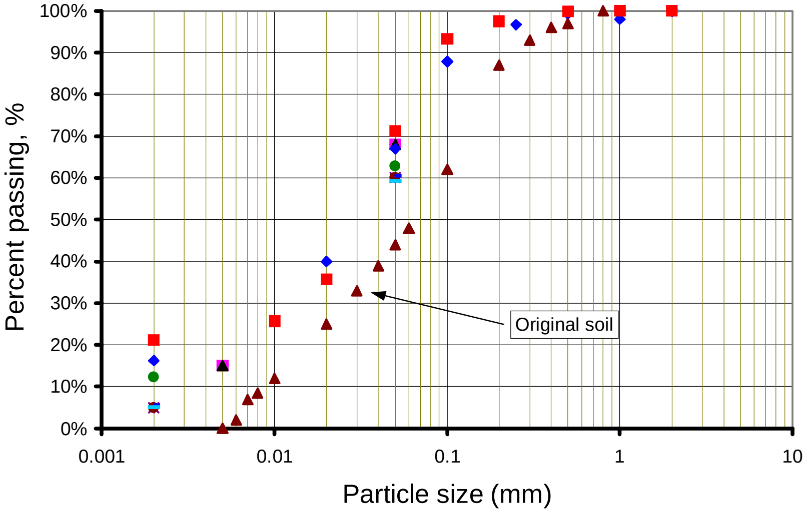

Figure 12 Grain-size distributions selected from the SoilVision database similar to the current soil

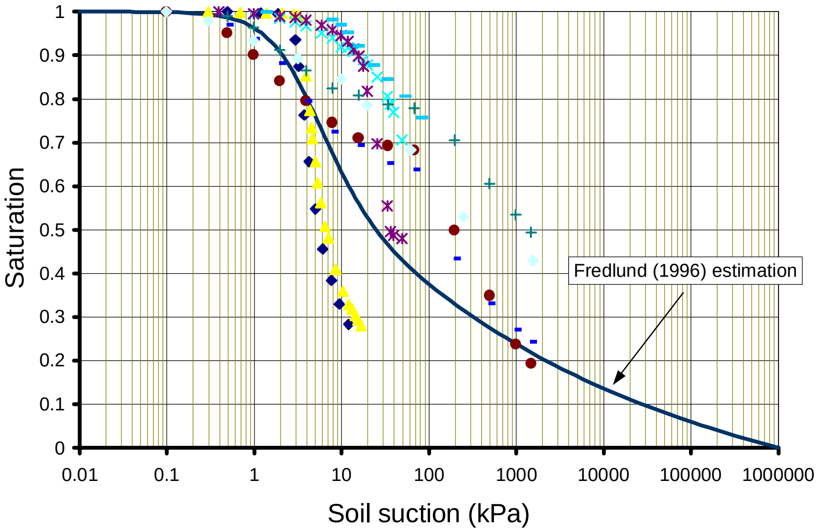

Figure 13 Comparison between the estimated and experimentally measured soil-water characteristic curves selected in the query

Analysis of the problem can now begin with the functions now provided by SoilVision. The soil property functions were input into the program SEEP/W and both the steady state, and the transient state problem were solved. The steady state analysis showed the location of the water table under the heavy rainfall experienced in Papau, New Guinea and the transient analysis showed the saturation levels in the tailings in the event of a long drought. The solution for the steady state analysis can be seen in Figure 15 while the solution for the transient state analysis can be seen in Figure 16.

Potential for Improvement in Engineering Implementation

The soil-water characteristic curve (relationship between water content and suction) has become of great value in estimating unsaturated soil property functions. The characterization of seepage, for example, in terms of a hydraulic head gradient and a coefficient of permeability function appears to be generally accepted (Fredlund, 1995). The use of nonlinear soil property functions for analyzing unsaturated soils problems appears to be gaining general acceptance. The soil-water characteristic curve then becomes a dominant relationship for understanding unsaturated soil behavior. This concept allows the soil-water characteristic curve can be used to compute approximate soil property functions for unsaturated soils.

The advantages to this approach are numerous. Firstly, an estimate of the unsaturated behavior of a certain soil is quickly available. The SoilVision knowledge-based database system alleviates this complexity. Secondly, the cost of estimation of soil behavior is greatly reduced. Testing of unsaturated soil property functions can cost thousands of dollars. A knowledge-based system provides estimates without the high cost of experimental testing. Thirdly, a knowledge-based system makes the estimation of behavior of unsaturated soils easy so that inexperienced professionals can work in this difficult area.

Acknowledgements

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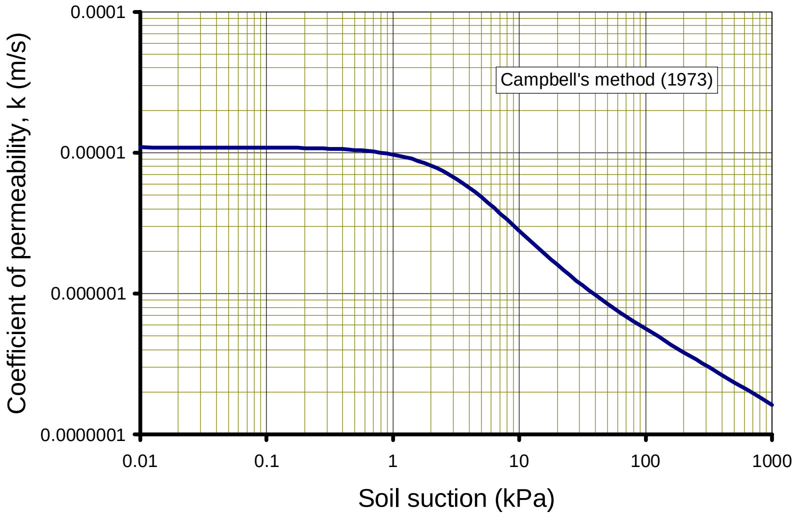

Figure 14 Estimated hydraulic conductivity curve for the mine tailings #11505.

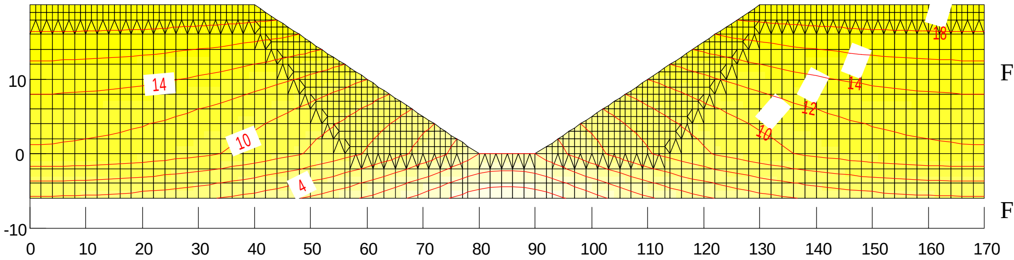

Figure 15 Results from SEEP/W of steady state analysis

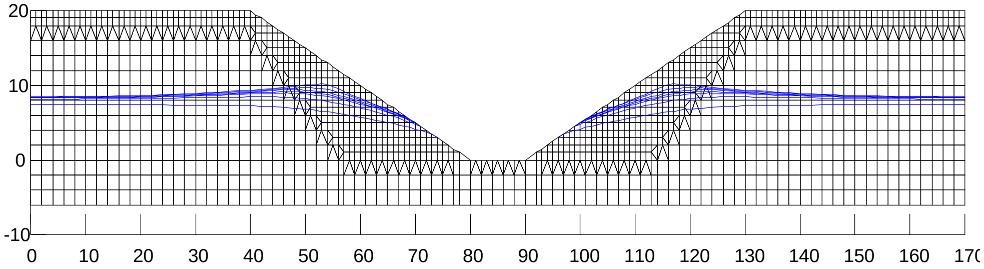

Figure 16 Results from SEEP/W of transient state analysis showing the location of the water table over time.

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For further information you may contact SoilVision Systems Ltd. at:
http://www.quadrant.net/soilvision