# Estimation of Hydraulic Properties of an Unsaturated Soil Using A Knowledge-Based System

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## ABSTRACT

The implementation of unsaturated soil mechanics into practice comes at a time when the scientist is accepting a new soil mechanics paradigm. Computers and numerical modeling play a dominant role in responding to 'What if--- ?' scenarios. For many problems involving unsaturated soils, it is necessary to be able to input approximate unsaturated soil property functions into the numerical model. For many problems, these functions can be approximated from either a knowledge of the soil-water characteristic curve or the grain size distribution of the soils involved. Databases of previous test data, along with a knowledge-based system becomes an important part of determining the necessary input soil property functions This implementation procedure deviates somewhat from historical classical soil mechanics procedures but has proven to be an acceptable procedure for the modeling of soil behavior.

## Introduction

The characterization of unsaturated soil behavior in terms of two independent stress state variables appears to be generally accepted as evidenced from the proceedings of the First International Conference on Unsaturated Soils, Paris, France (1995). Theories have been formulated for the classic areas of i) seepage, ii) shear strength, and iii) volume change, for unsaturated soils (Fredlund, 1979). Constitutive relationships have been proposed for the classic areas of soil mechanics for saturated and unsaturated soils and in each case the soil properties become soil property functions.

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). 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 paper 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.

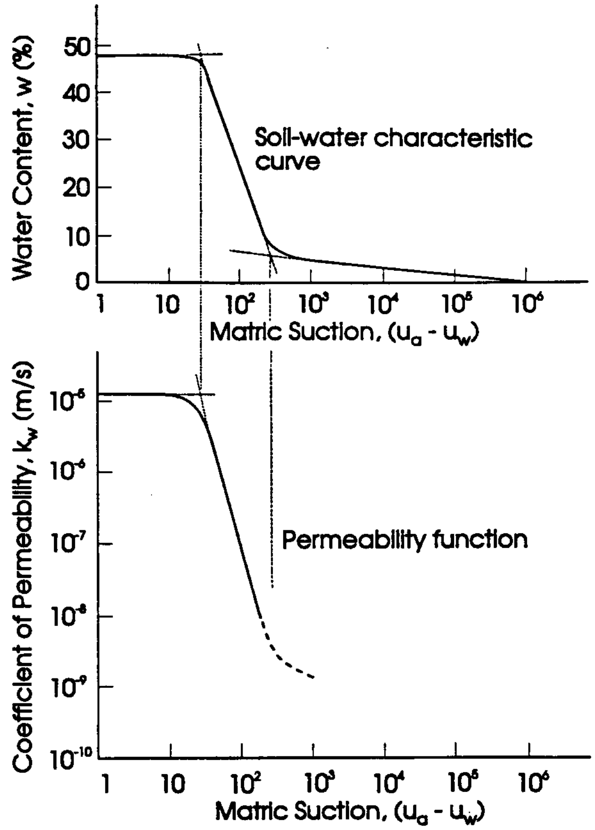


**Figure 1 Visualization of the relationship between the coefficient of permeability function and the soil-water characteristic curve.**

## 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: $\theta_w$ = volumetric water content, $\theta_s$ = volumetric water content at saturation, e = 2.718……, ( $u_a$ - $u_w$ ) = soil suction, $a_f$ = soil parameter approximating the air entry of the soil, $n_f$ = 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, an examination should be made of the possibility of using grain size distribution classification test data for the prediction of the soil-water characteristic curve.

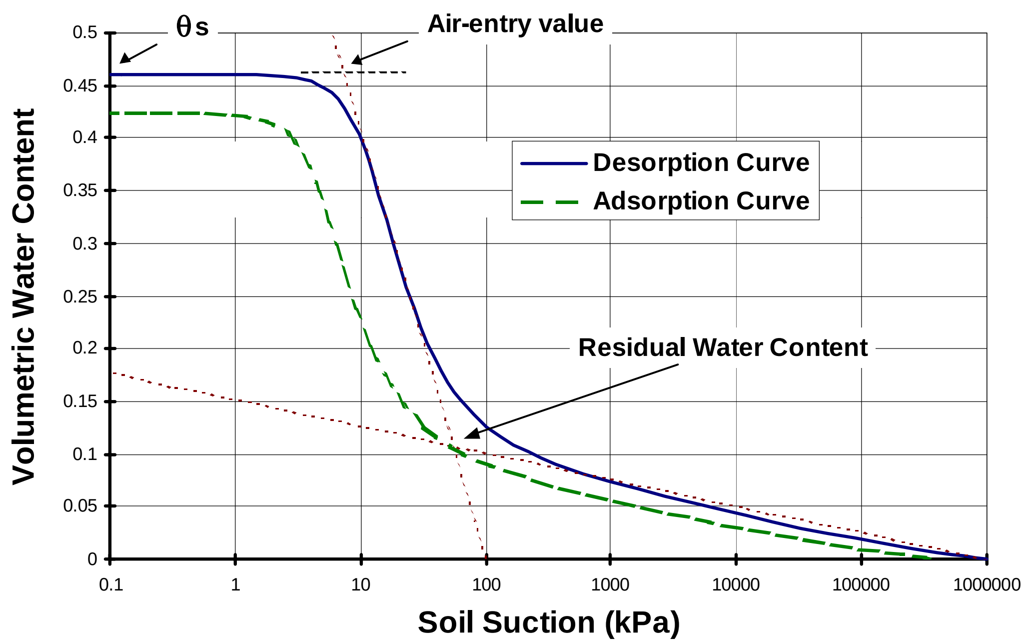


**Figure 2 Definition of variables associated with the soil-water characteristic curve.**

## Approaches to Obtain Unsaturated Soil Property Functions

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 predicted soil-water characteristic curve with experimental data is shown in Fig. 5. While there may be a further reduction in the accuracy of the predicted unsaturated soil property function, the engineer must assess whether or not the approximated soil function is satisfactory for the analyses which must be performed.

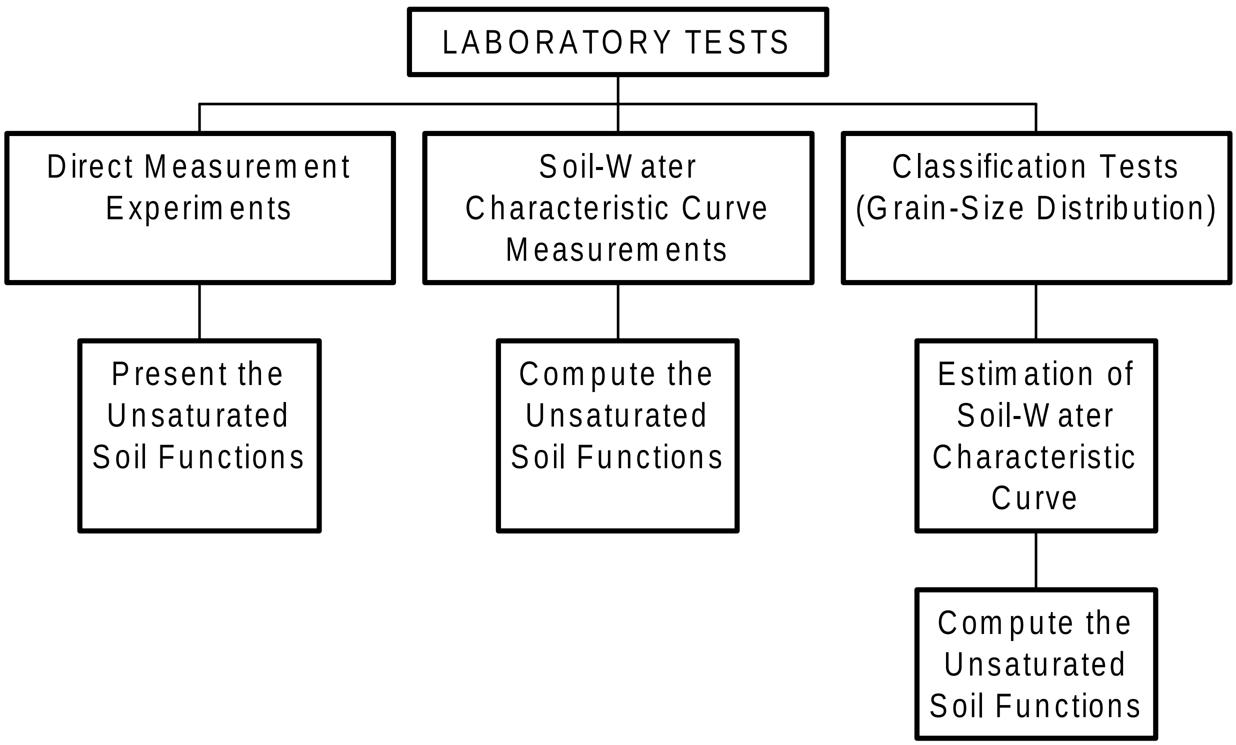


**Figure 3 Approaches that can be used in the laboratory to determine the unsaturated soil properties.**

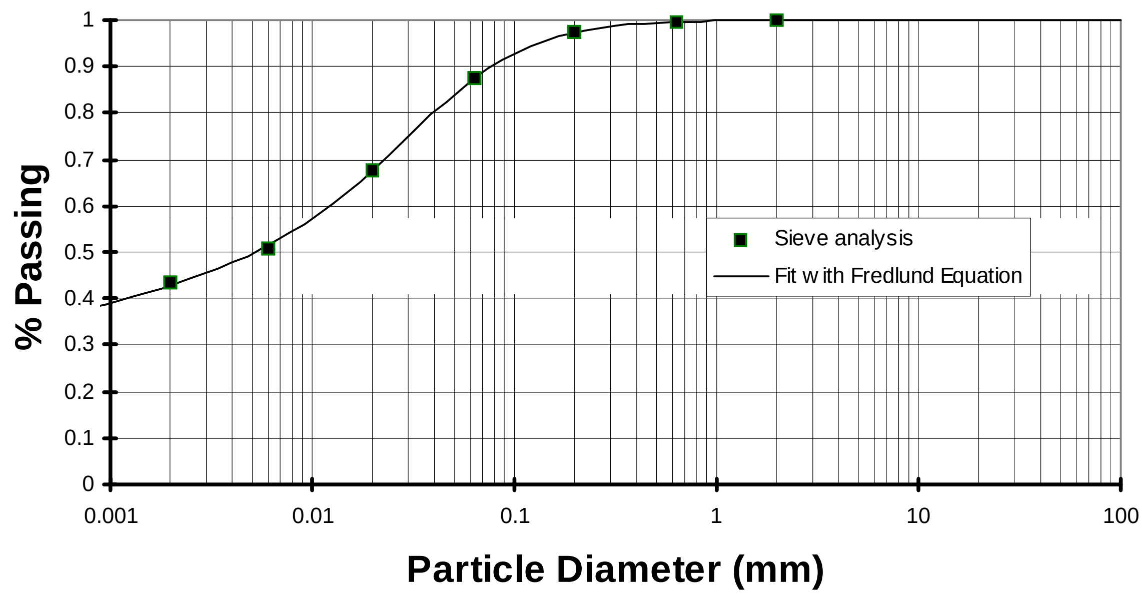


**Figure 4 Grain-size distribution curve fit for a Silty Clay (#10838).**

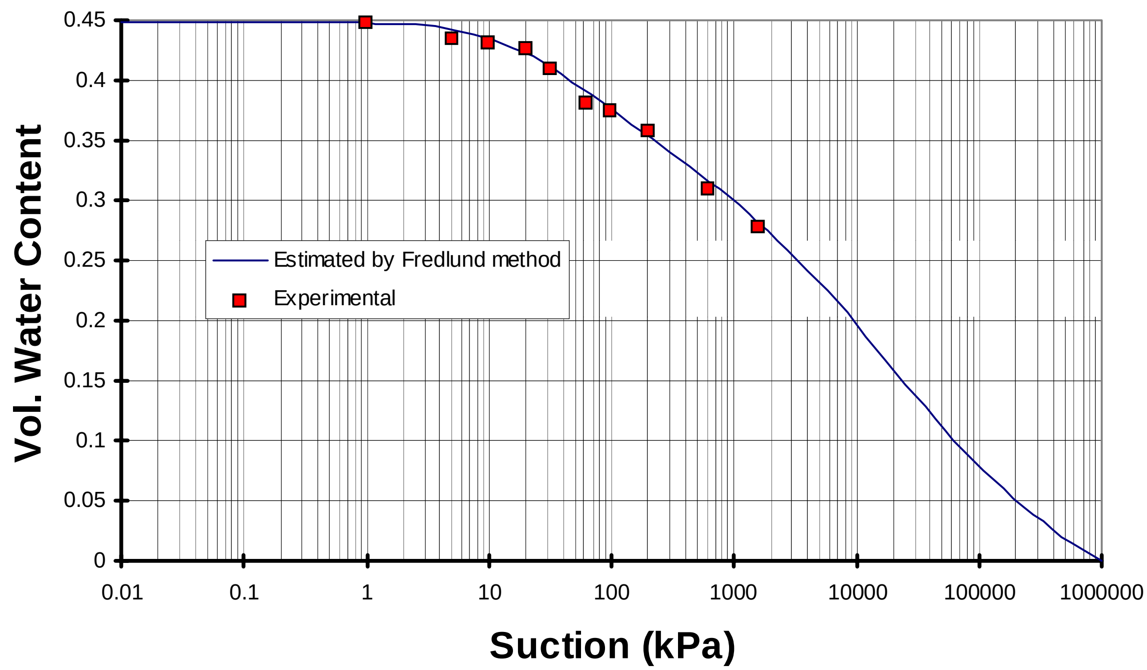


**Figure 5 Comparison between experimental and predicted soil-water characteristic curves for Silty Clay (#10838).**

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.

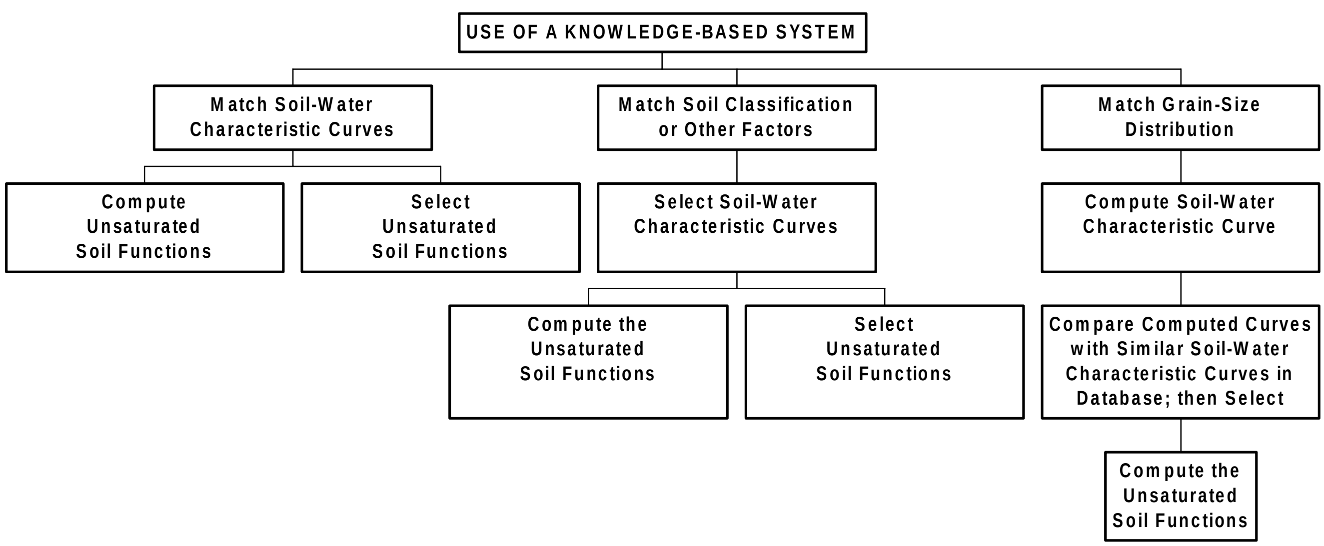


**Figure 6 Approaches that can be used to determine the unsaturated soil property functions when using classification tests and a data base.**

The third suggested procedure involves working directly with the measured grain size 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. 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.

## Example - 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.

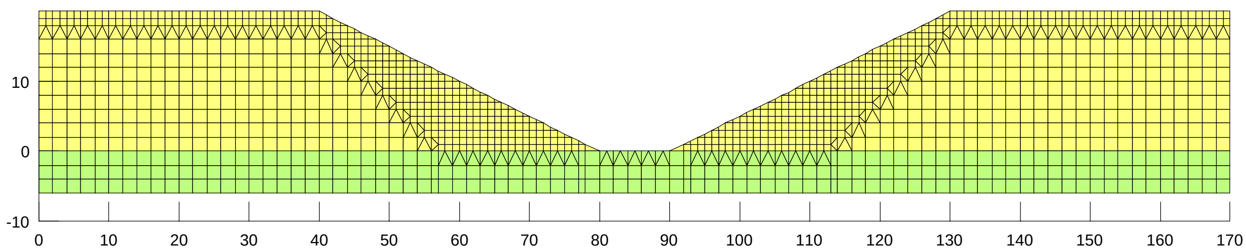


**Figure 7 Problem definition for site in Papua New Guinea**

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.

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.

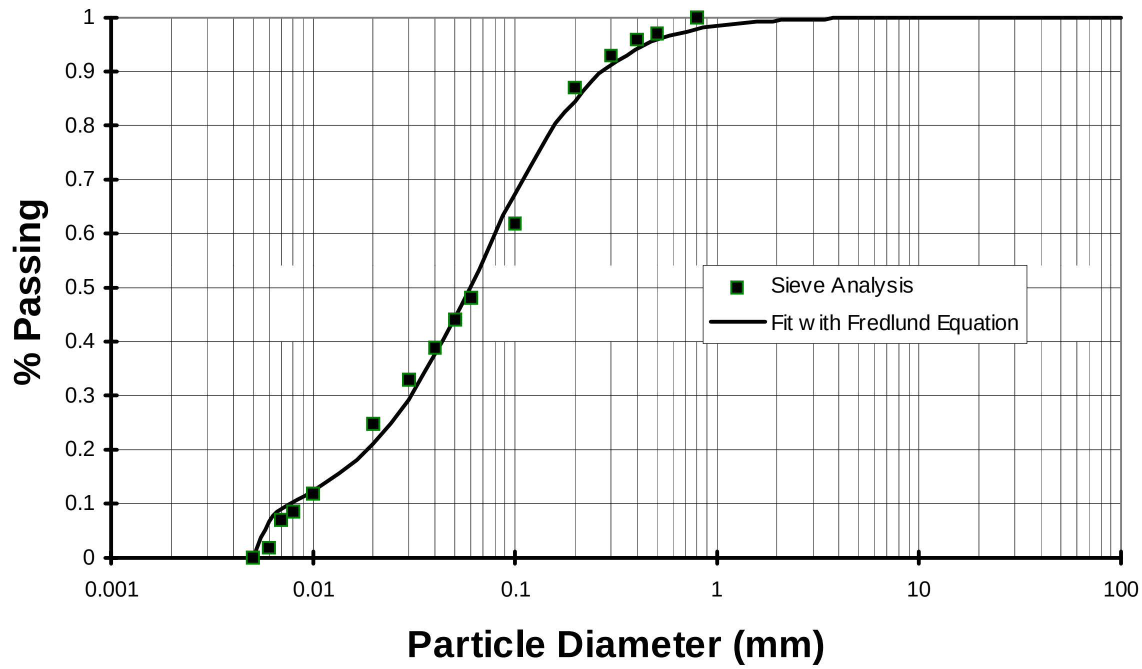


**Figure 8 Given grain-size distribution for the mine tailings #11505**

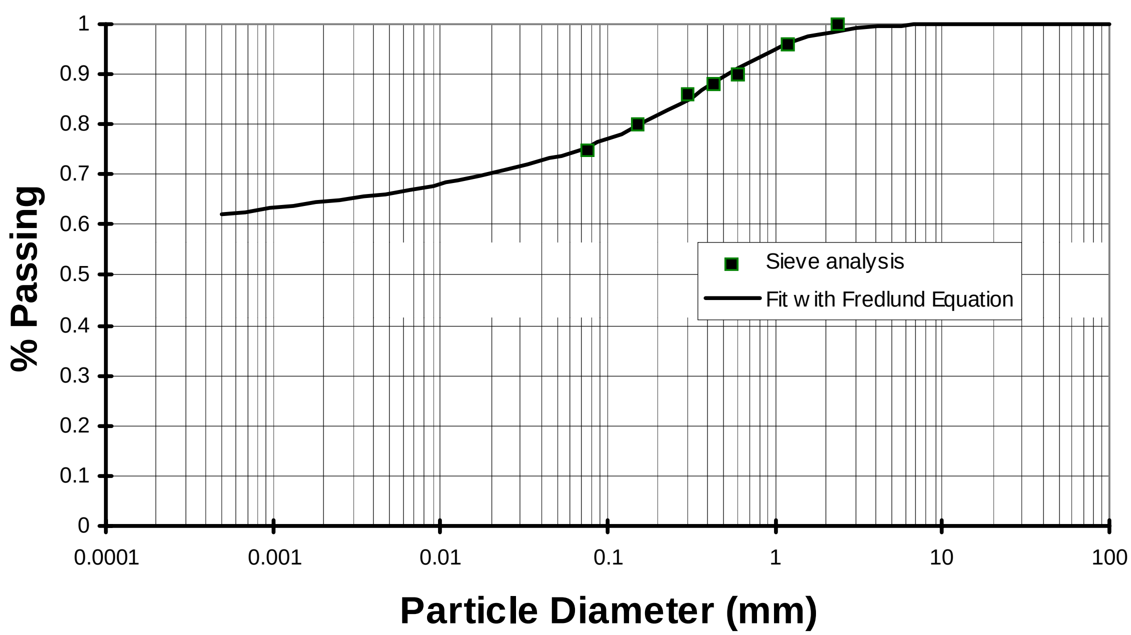


**Figure 9 Given grain-size distribution for underlying clay #11638**

The first task at hand is to input the given information into SoilVision. This is accomplished by inputting information on page one of the main soils form, page two of the main soil form, and the geography page of the soil form. The soil texture is left blank because that will be determined by the grain-size distribution. Page one of the main soil information form can be seen in Figure 10. Secondly, the grain-size information must be input. A short description of the grain-size distribution and then the points on the distribution must be entered. The experimental points are then fit with an equation. The final fit can then be evaluated by graphing the function.

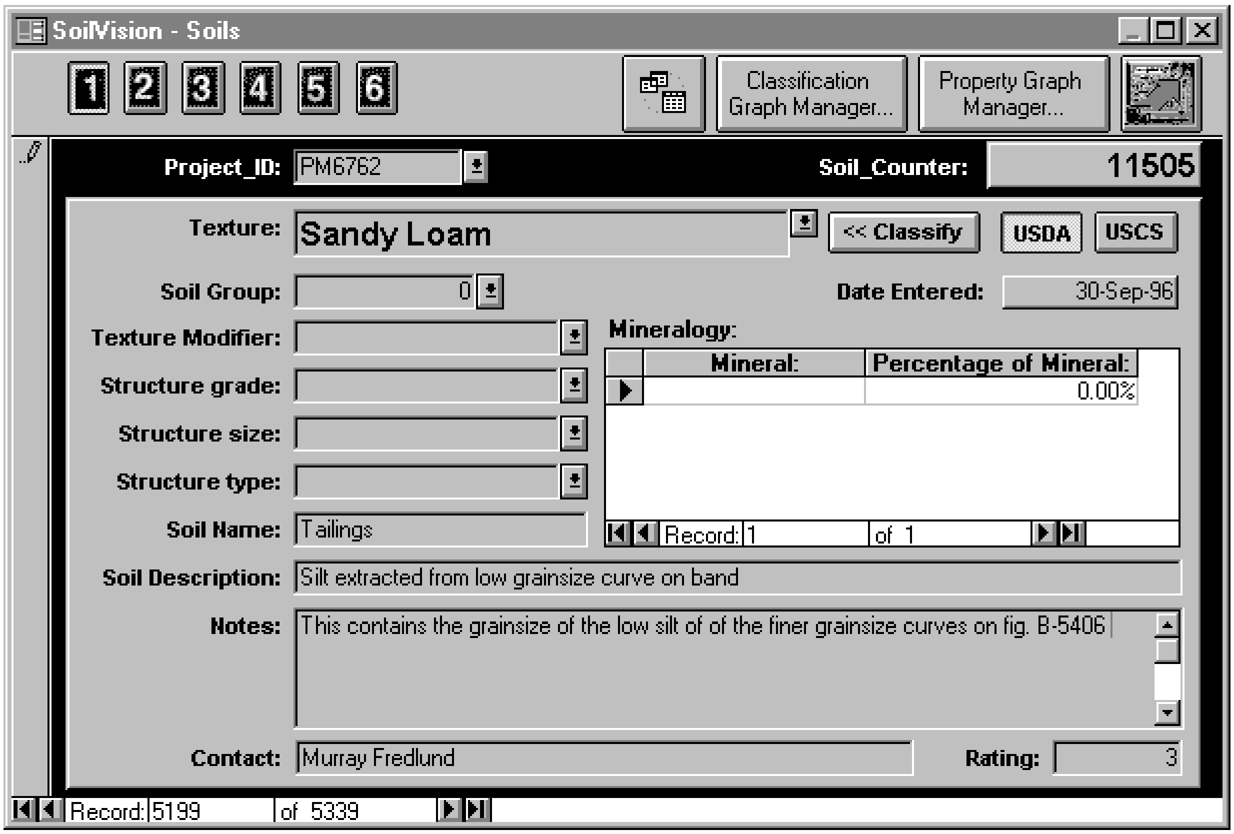


**Figure 10  Sample input form for soils information**

The next step is to classify the soil. Classification is necessary for SoilVisions Rule Base to properly extract similar soils from the database. Classification can be automatically accomplished by pressing the ***classify*** button on the main soils page in SoilVision. Classification by the USDA method classifies the mining tailings as a sand.

The soil-water characteristic curve must now be predicted. The most accurate way of estimating the soil-water characteristic curve is by the algorithm provided within SoilVision. The algorithm estimates the soil-water characteristic curve from volume-mass properties and the grain-size distribution of a soil. An estimate of the Packing Porosity (not to be confused with the porosity of the soil) is needed to control the prediction. The Rule Base can estimate the Packing Porosity by pulling all soils in the system on which the prediction algorithm has been trained. The Rule Base then shows the possible variance of the Packing Porosity. Once the Packing Porosity is chosen, the soil-water characteristic curve may be predicted. A packing porosity of 0.40 was chosen for the mine tailings and this packing porosity produced a soil-water characteristic curve as shown in Figure 11.

The predicted soil-water characteristic curve may be viewed by opening the drying soil-water characteristic curve form. The graph shows the predicted points on a graph of volumetric water content versus soil suction. It is now necessary to fit an equation through the series of predicted points. A fit can be accomplished by entering a description, selecting a fit equation, and initiating the fit algorithm. The fit and predicted soil-water characteristic curves may now be graphed. A graph of the predicted and fit soil-water characteristic curve can be seen in Figure 11. van Genuchten's equation was used to fit the predicted points of the soil-water characteristic curve. If some uncertainty exists regarding the prediction, the predicted results can be compared to experimental results in the database by querying the database and graphing groups of experimentally measured soil-water characteristic curves. The database contains over 600 soils with matching experimentally measured grain-sized distributions and soil-water characteristic curves.

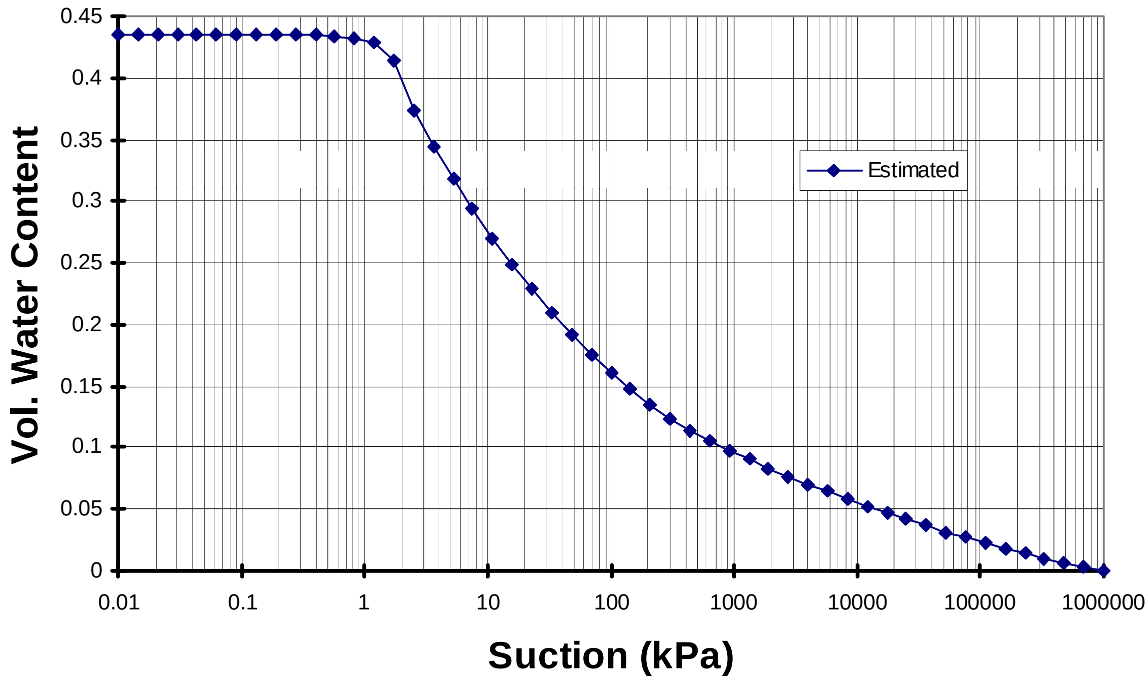


**Figure 11 Estimated soil-water characteristic curve for mine tailings #11505**

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 12.

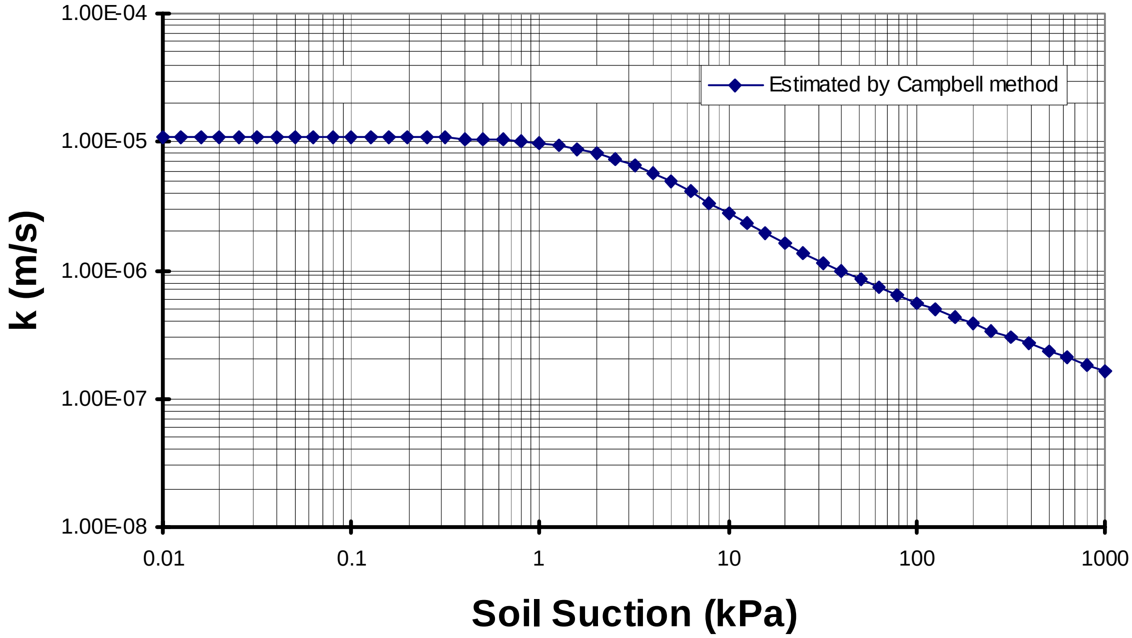


**Figure 12  Estimated hydraulic conductivity curve for the mine tailings #11505**

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 (from Geo-Slope International) 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 13 while the solution for the transient state analysis can be seen in Figure 14.

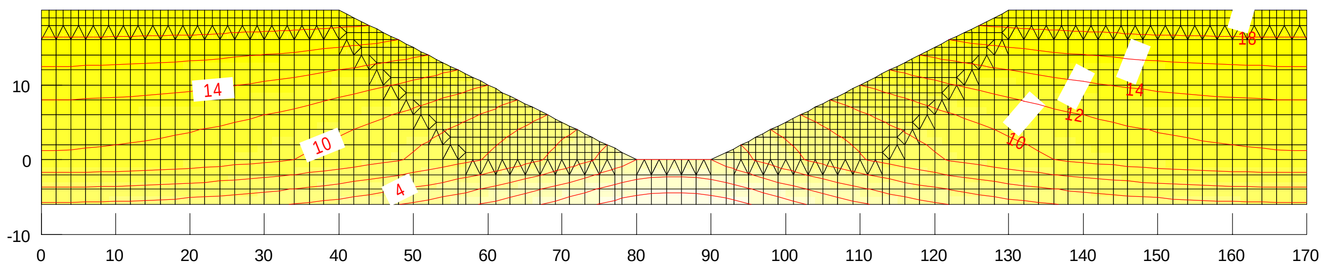


**Figure 13 Results from SEEP/W of steady state analysis**

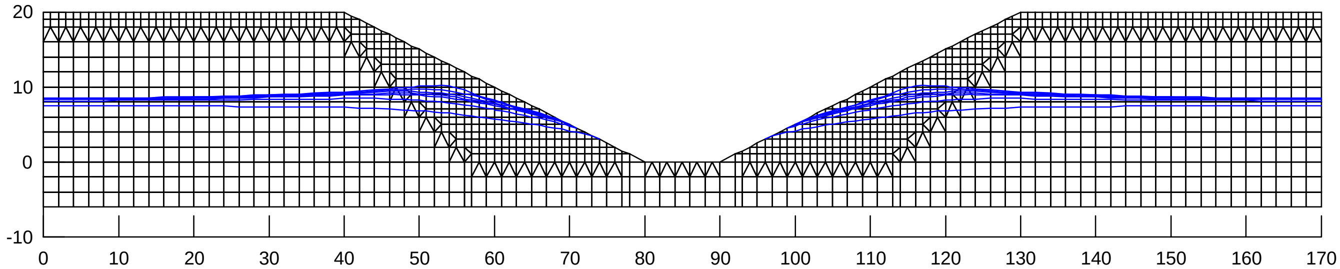


**Figure 14 Results from SEEP/W of transient state analysis showing the location of the water table over time**

## Conclusions

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 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 can be used to compute approximate soil property functions for unsaturated soils. Several approaches can be taken towards the determination of unsaturated soil property functions.

The advantages to this approach are numerous. 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 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. 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.

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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. It was shown that a knowledge-based database system can successfully be used to estimate the soil functions necessary for this type of analysis.

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