A New Soil-Water Characteristic Curve Device

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ABSTRACT: The inabilities to measure volume change, to simulate overburden pressure, and to continually monitor water content without disassembling of the apparatus are among the limitations of pressure plate devices commonly used to experimentally apply matric suction to a soil. These limitations affect the experimental determination of soil-water characteristic curves (SWCCs). The authors have developed a device that has greater flexibility with regard to applying matric suction and following a variety of net normal stress paths. The stainless steel cell is called the "Fredlund SWCC" device and it allows the application of field overburden pressures for specimens up to 75mm in diameter. The specimen volume change and water content can be continuously measured without dismantling the device. The device can measure both the drying and wetting SWCCs. The apparatus also allows for measurement of diffused air, removal of diffused air, and pressure compensation on the loading shaft. Also, the Fredlund SWCC device can be used for the measurement of *in situ* suction on undisturbed or compacted specimens. Details of the device and examples of data generated are presented in this paper. The versatility and flexibility exhibited by the device allow practitioners and researchers to conveniently and efficiently measure the SWCC that can then be used for the determination of unsaturated soil property functions.

1 INTRODUCTION

The soil-water characteristic curve (SWCC) defines the relationship between water content and soil suction in unsaturated soils. The amount of water in a soil can be expressed in one of three different ways: gravimetric water content (w); volumetric water content (θ_w); or degree of saturation (S). Soil suction (ψ), or 'total soil suction,' corresponds to the free energy of the soil water and is comprised of two components identified as matric suction, $(u_a - u_w)$, and osmotic suction, (π) as shown by Equation 1.

$$\psi = (u_a - u_w) + \pi \qquad (1)$$

The Fredlund SWCC device applies or measures the matric suction, which is the difference between pore-air pressure, (u_a) and pore-water pressure, (u_w). Matric suction is generally viewed as related to the capillary phenomenon, while osmotic suction is related to the presence of dissolved salts in the pore-water. For most of the engineering applications, it is the matric suction that is of primary importance. However, there may be cases where the osmotic suction might vary in either space or time and become important.

Three experimentally determined SWCCs for sandy, silty, and clayey soils are shown in Figure 1. The curves can be best fit using the Fredlund-Xing equation (Fredlund and Xing, 1994), which yields SWCC curves that end at 1,000,000 kPa.

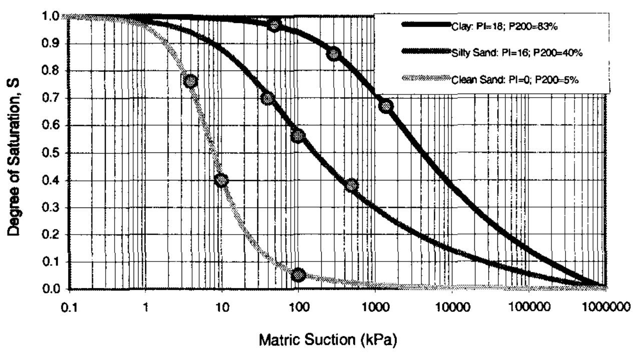

Figure 1. Experimentally determined SWCCs (Perera et al. 2005).

The SWCC of a soil is required when solving engineering problems involving unsaturated soils. Consideration of the unsaturated soil portion of the soil profile is becoming more and more common in engineering practice. For example, the SWCC data is almost always used when modeling unsaturated moisture movement through highway pavement structures, earth dams, and ground slopes. The unsaturated hydraulic conductivity, (k_{unsat}) is generally estimated from the SWCC curve. Suction is a fundamental stress state variable (Fredlund and Rahardjo, 1993) and is also used in the estimation of shear strength and volume change functions for unsaturated soils.

The objective of this paper is to introduce the newly developed unsaturated soil testing apparatus, describe the testing procedure, and present some test data generated using the device.

2 THEORETICAL BACKGROUND

Soil suction, commonly referred to as the free energy state of soil water, can be written in terms of the partial vapor pressure of the soil water. The partial vapor pressure is related to relative humidity. Therefore, a relationship between soil suction, ψ, and relative humidity (*RH*) can be expressed in kPa as in Equation 2 for a reference temperature of 20 °C. Detailed discussion of this topic can be found in Fredlund and Rahardjo (1993). Figure 2 provides a graphical representation of Equation 2.

$$\psi = -135{,}022 \ln (RH) \qquad (2)$$

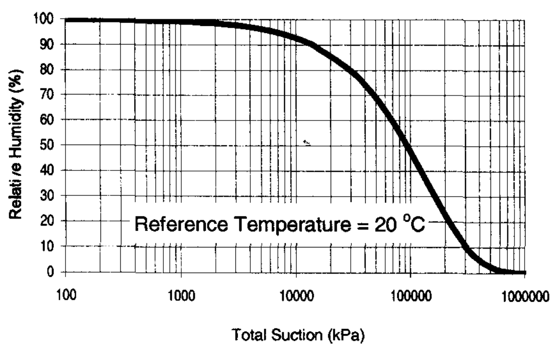

Figure 2. Relative humidity versus total suction (Fredlund and Rahardjo, 1993).

SWCCs are sigmoidal in shape, similar to the *RH* versus ψ curve shown in Figure 2. In a SWCC, the x–axis represents the soil suction on a log scale, while the y–axis represents the water content expressed, for example, as S, (Figure 1). Fredlund and Xing (1994) proposed a four-parameter sigmoidal curve for representing the entire SWCC (Equation 3). The Fredlund and Xing equation can be best-fit to experimental data points for the determination of the equation parameters.

$$S = C(\psi)\left\{ 1 \Big/ \ln\left[\exp(1) + \left(\frac{\psi}{a}\right)^{b} \right]^{c} \right\} \qquad (3)$$

where: $C(\psi) = 1 - \ln\left[1 + \left(\frac{\psi}{h_r}\right)\right] \Big/ \ln\left[1 + \left(\frac{10^6}{h_r}\right)\right]$,

ψ = suction in kPa,
θ_w = volumetric water content,
θ_s = saturated volumetric water content,
a = a soil parameter which is primarily a function of the air entry value of the soil in kPa,
b = a soil parameter which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded,
c = a soil parameter which is primarily a function of the residual water content, and
h_r = a soil parameter which is primarily a function of the suction at which the residual water content is reached in kPa.

SWCCs exhibit hysteresis, which means that the position of the curve depends on whether the specimen is drying or wetting. The 'drying curve' is generally measured by starting the test using a saturated soil specimen and applying increasing pressure increments. Once the 'drying curve' is complete, pressure decrements can be applied to the same specimen to obtain the 'wetting curve'. The 'wetting curve' is always located below the 'drying curve' as shown in Figure 3.

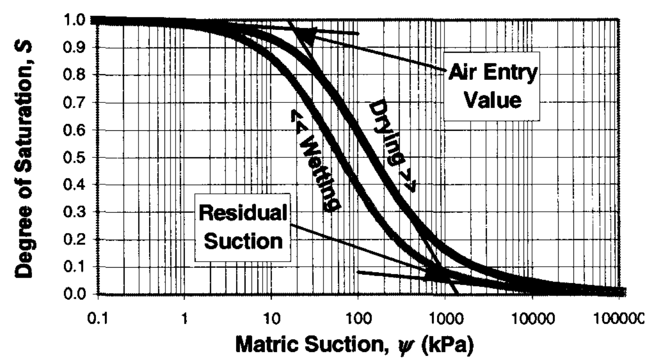

Figure 3. Typical drying and wetting SWCCs.

3 THE FREDLUND SWCC DEVICE

The Fredlund SWCC device is a pressure plate device that comes with 3-inch diameter interchangeable ceramic disks (i.e., high air-entry disks). The device consists of a pressure cell assembly and a pressure panel as shown in Figures 4 and 5.

There are several features built into the Fredlund SWCC device that help make the testing procedure simple, accurate, and reliable. The field overburden pressure can be simulated by applying vertical loads. The apparatus has the ability to measure the water content of a soil specimen without dismantling the apparatus during testing. The water released (or absorbed) from the specimen is measured using two volume indicator tubes on the pressure panel. The soil specimen is placed on a saturated ceramic disk, which is embedded in a recess filled with water below the bottom plate of the apparatus. The recess is connected to the two volume indicator tubes on the pressure panel via plastic tubing. The volume indicator tubes are graduated to read the amount of water released or absorbed during a test.

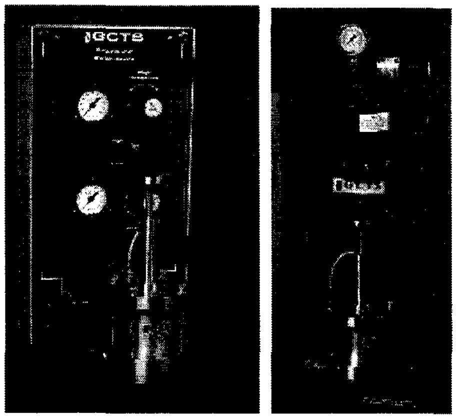

Figure 4. The Fredlund SWCC Device (left) and load frame (right).

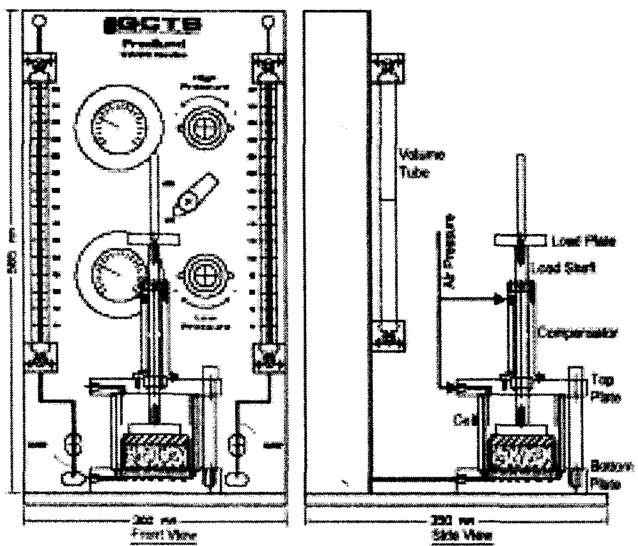

Figure 5. Schematic of The Fredlund SWCC Device.

Diffusion of air into the recess below the ceramic disk during testing introduces a volume error, and therefore the diffused air bubbles should be removed. This is accomplished by flushing the system using an air pump. Flow is alternated until all the air bubbles are removed. If desired, the volume of diffused air can be measured by comparing the volume tube readings before and after flushing.

Another important feature of the Fredlund SWCC device is its ability to measure overall volume change of the soil specimen during the test. The movement of the load plate indicates the movement of the top surface of the soil specimen. The movement of the load plate can be measured using a caliper, dial gauge, or an LVDT. If the specimen does not contract diametrically, (which is typically the case when a net normal stress is applied), the volume change can be computed based on vertical movements. Otherwise, the overall volume is difficult to compute if there is radial contraction of the specimen from the confining ring. The Fredlund SWCC device is equipped with a miniature heater that can maintain the chamber temperature constant and slightly above ambient temperature. This feature helps prevent condensation of water vapor.

Only one soil specimen is needed to determine the entire SWCC, providing a simple procedure and more consistent results. The pressure panel comes with dual pressure gauges for maintaining high accuracy in both low and high suction ranges. The system needs a clean dry air supply that is capable of producing pressures up to 1,500 kPa (220 psi). A list of accessories needed for assembling the Fredlund SWCC device and carrying out the tests is shown in Table 1.

Table 1. Accessories needed for SWCC testing

Accessory	Use / Remarks
Dead Weights	100 g, 500 g, 1 kg, 2 kg, 5 kg, 10 kg
Ceramic disks	1, 3, 5, and 15-bar
Water supply	demineralized water
Electronic balance	accuracy of 0.01 g (at least 500 g capacity)
Metal rings	to hold the specimen
Oven	for water content determination
Glass/plastic plates	for sample preparation
Air compressor	pressure source providing up to 1,500 kPa
Plastic containers	for sample and ceramic disk saturation
Vernier caliper	for specimen height change measurements
Spring clipper	for taking height measurement
Hydraulic jack	for extrusion of tube samples
Porous stones	for sample saturation process
Tools	allen-wrenches, screwdrivers etc.

A component of the apparatus identified as the "compensator" is used to balance the uplift force generated by internal air pressure acting on the loading shaft. The loading shaft moves up and down through the compensator on a set of O-rings generating minimal friction. Weights can be applied to compensate for the friction on the loading shaft. Vertical loads up to 10 kN can be applied using the load frame shown in Figure 4.

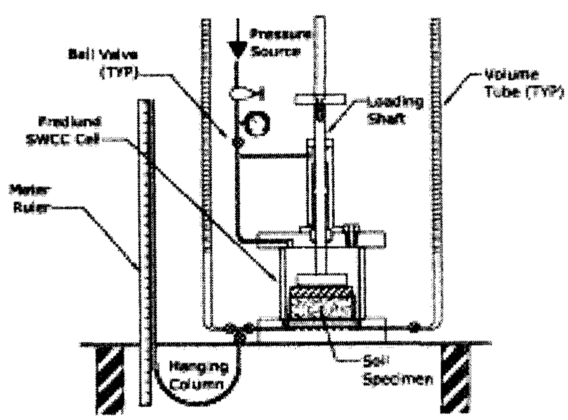

Figure 6. The Fredlund SWCC device with "hanging column".

An optional feature available with the Fredlund SWCC device is the "hanging column" accessory, which enables the application of low suctions to soil specimens. A schematic of the Fredlund SWCC device with the hanging column is shown in Figure 6.

4 SAMPLE PREPARATION

Tube samples or disturbed samples can be used in preparing test specimens for the SWCC test. The Fredlund SWCC device can accommodate various sizes of specimens ranging between 62 mm and 75 mm in diameter. The height of the specimen can be between 12 mm and 25 mm.

4.1 *Preparation of Compacted Specimens from Disturbed Samples*

Disturbed samples collected in the field should be prepared for SWCC testing by compaction into the rings. The portion of soil passing No. 4 sieve (Minus No. 4) is used in this procedure. The amount of sample required for one specimen is determined based on the *in situ* dry unit weight of the Minus No. 4 fraction. This is estimated using the assumption that the specific gravity (G_s) of the Plus No. 4 and Minus No. 4 materials are the same, and the Minus No. 4 material completely fills the voids formed by the Plus No. 4 material of the soil mass in the field.

4.2 *Preparation of Undisturbed Specimens from Tube Samples*

Thin-walled tube samples obtained from field sampling should be carefully extruded into thin-walled stainless steel or brass rings prior to testing as described below.

Partially extrude the tube sample using a hydraulic jack and a steel frame. Metal plates and spacers are required for the sample extrusion process. Typically, the height of the SWCC specimen is 25 mm (1 inch), and therefore, 30 mm (1.25 inches) of extrusion should be adequate. Place the specimen ring on the top of the extruded soil and press the ring vertically down into the soil by means of a metal plate until the ring is full. The internal diameter of the tube should be the same or larger than the specimen ring. Smaller diameter specimen rings can be used with fine-grained soils. The ring filled with soil from the tube should then be separated from the tube, and both ends trimmed.

5 SUMMARY OF TEST METHOD

The Fredlund SWCC device is primarily designed to determine the SWCC of a soil (Section 5.1). However, in addition, the device can be effectively used to measure the *in situ* suction of a soil element in the field (Section 5.2).

5.1 *Determination of SWCCs*

Soil specimens are saturated prior to each test by partially submerging the specimens in a bath of water to attain the maximum possible saturation. The saturated soil specimen is placed on a saturated ceramic disk and mounted on the bottom plate. The ceramic disk is held in place by means of four mini-screws attached to the bottom plate. The pressure cell is assembled as shown in Figure 7, and the determination of drying curve of the SWCC is begun. Alternatively, the SWCC can be determined by starting the test at the in-situ water content.

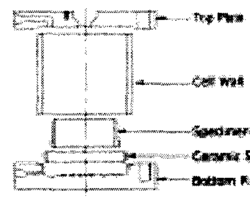

Figure 7. Schematic of pressure cell assembly.

The ceramic disk acts like a semi-permeable medium and allows water, but not air, to pass through the disk up to a rated air pressure value (i.e., air entry value of the ceramic). The bottom of the ceramic disk is maintained more or less at atmospheric pressure by connecting the drain holes to two tubes filled with water. A vertical load is applied to the soil specimen, using either dead weights placed on the load plate or a load applied using a load frame. The applied air pressure represents the applied matric suction. In response to the applied suction the water will move out from the soil specimen and drain through the ceramic disk until the equilibrium is established. The water level in the volume indicator tubes will show the amount of water released and cease to move once equilibrium is attained. Following equilibrium, the water levels in the volume indicator tubes are recorded. It is also possible for air to diffuse through the ceramic disk and collect below the bottom of the ceramic disk. Diffused air should be flushed before final readings are taken on the volume indicator tubes. The water content of the specimen is computed based the initial water content using the volume indicator tube readings. The overall volume change of the soil specimen is measured by taking initial and final distance measurements between the load plate and top plate of the cell using calipers or an attached dial gauge. The procedure is repeated for the next air pressure increments to obtain a series of data points on the SWCC. When the applied value of u_a is very small the height of the water column in the volume tubes, u_w, may not be negligible and should be subtracted from u_a to get soil suction.

The procedure can also be repeated by applying pressure decrements to obtain the 'wetting' curve. At the end of the test, the soil specimen is removed from the cell and its water content is determined by oven drying the specimen.

5.2 *Optional Test Method for Measuring In Situ Suction*

The Fredlund SWCC device can be used, indirectly, to measure the soil suction of an element of soil in the field. By this procedure a high quality undisturbed sample is extracted and brought to the laboratory and transferred into an SWCC ring, without loss or gain of water. The initial moist mass of specimen and ring are measured before insertion into the SWCC chamber. An initial estimate of the field soil suction is applied as u_a and the volume change tubes are observed to detect and prevent water content change (Δw). By varying u_a it is possible to make the change in water content zero or essentially zero. Close attention is required during the first two or three hours and then adjustment in u_a can be made at greater time intervals. Once the specimen shows no further tendency for water content change, the applied u_a and u_w may be used as a fairly good estimate of the *in situ* soil suction. This estimate can be further refined as follows.

At the end of the test the specimen is carefully and completely removed from the apparatus and weighed with the ring. Any difference in the final and initial masses quantifies the failure to hold the water content constant. This difference, if any, can be corrected for as follows. Plot the measured suction and the final S of the specimen on a graph such as Figure 8, and trace out a small segment of the SWCC that passes through the plotted point. Use Δw measured as described above to compute a corresponding ΔS and travel along the SWCC to the initial S and read off an adjusted measured soil suction for the field. This procedure is of course more applicable to silts and clays than to non-plastic sands, for which undisturbed samples are very difficult to obtain. For this last category of soils, it is possible, with some loss of accuracy, to compact a specimen in the laboratory to the density and S believed to exist in the field and then proceed with this compacted specimen as if it were an undisturbed specimen. This approach (using compacted non-plastic sands) requires the assumption that any differences in the fabric of the compacted specimen and *in situ* element of sand does not seriously affect the soil suction.

In this connection the hanging column can be used to measure very small suctions in the specimen as follows. Rather than using variable u_a and more or less constant u_w to null out any tendency for water content change, the "hanging column" can be used to arrest water content change tendency by simply raising or lowering the movable half of the hanging column so as to keep the reading constant. Note that this application of hanging column is not necessary unless it is desired to measure an initial suction which is expected to be less than about 5 kPa. For higher values of initial suction the standard procedure of varying u_a with an air pressure regulator as described above can be used.

5.3 *Selection of Ceramic Disk*

Four different ceramic disks are available for use with the Fredlund SWCC device. These disks are capable of withstanding 100, 300, 500, and 1,500 kPa of air pressure. The appropriate ceramic disk is selected based on the type of soil being tested. Table 2 can be used as guidance for making this selection.

Table 2. Selection of ceramic disk.

Type of Soil	Rating of Ceramic Disk (kPa)
Clean Sand	100
Silty Sand, Clayey Sand	300
Sandy Silt, Sandy Clay	500
Clay	1,500

5.4 *Selection of Target Suction Values*

The target suction values to be applied to the specimen during the course of testing should be determined beforehand. It is practical to select suction values corresponding to S between 10% and 90%, which depend on the type of soil. For example: for a granular soil, appropriate target pressures could be 5, 50, 100, and 500 kPa, while for a fine-grained soil the target pressures might be 20, 100, 500, and 1,500 kPa. The following paragraph provides a simple way to determine these target values.

If the soil is granular, determine the D_{60} value from the grain-size distribution. If the soil is fine-grained, determine the weighted PI (*wPI*) of the soil, where *wPI* = Percent Passing No. 200 Sieve (expressed in decimal) x (*PI*). Based on D_{60} or *wPI*, select the corresponding curve from the family of SWCCs shown in Figure 8, where D_{60} curves represent 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 mm and *wPI* curves represent 0.1, 3, 5, 10, 15, 20, 30, 40, and 50. The family of curves provides a rough but quick estimate of the SWCC. Based on research conducted at Arizona State University (Perera et al., 2005), an SWCC prediction model was developed that used the grain-size distribution and index properties. This model can be used to obtain a first approximation of the SWCC.

It may not always be possible to obtain a wide range of S for fine-grained specimens because the actual curves might extend well beyond the 1,500-kPa limit. For fine-grained soils, the complete

SWCC can be obtained by combining the pressure plate test method with the desiccator method.

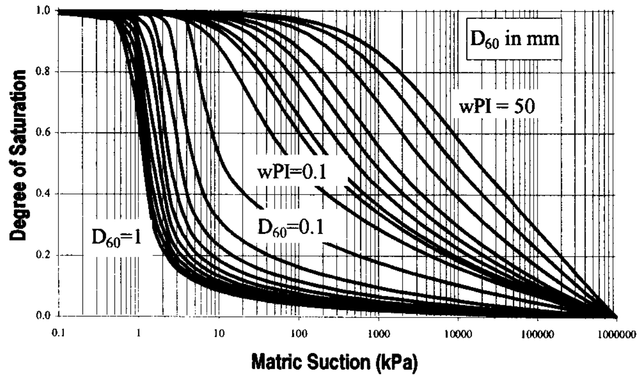

Figure 8. Family of SWCCs (Zapata, 1999).

6 ACTUAL TEST DATA

The Fredlund SWCC device has been successfully used on a major research project carried out at Arizona State University (Perera, 2003). About 100 soil samples were collected from 30 sites located throughout the United States. The samples included both disturbed, granular samples and undisturbed, fine-grained samples for which the SWCC was measured using a three-point method. The generated experimental data points were fitted with the Fredlund and Xing curve (Equation 3, Fredlund and Xing, 1994). Figure 1 presents three such experimentally obtained SWCCs using the Fredlund SWCC device. Based on the experimental data, two predictive models were developed:

Model I: For the prediction of long-term water content beneath highway pavements (Perera et al. 2004), and

Model II: For the prediction of SWCC of a soil based on grain-size distribution and index properties (Perera et al. 2005).

7 CONCLUSIONS

The Fredlund SWCC device is useful in determining both drying and wetting SWCCs of any soil in the laboratory. Only one soil specimen is required to obtain the complete SWCC of the soil. The water content of the soil specimen can be determined at any point during the test without dismanteling the device. An *in situ* overburden pressure or any arbitrarily chosen stress can be applied during the testing by applying vertical loads to the specimen. The volume change of the specimen can be measured based on the movement of the vertical loading shaft. Diffused air can be flushed from beneath the ceramic disk. These features contribute to a convenient test procedure and reliable test results.

The maximum suction that can be applied using the Fredlund SWCC device is controlled by the highest available rating of the ceramic disk, (i.e., 1,500 kPa).

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