Indian Geotechnical Journal, 32 (3), 2002

Application of a Tensiometer for Estimating Soil-Water Characteristic Curve and Hydraulic Conductivity

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Introduction

Measurement of soil suction, Ψ, is essential for various projects such as road and railway embankments (Gourley and Schreiner, 1995), waste containment in landfill sites where the soil permeability is a function of Ψ (Rahardjo et al., 1995; Fredlund, 1995), for creating detailed guidelines for vegetation management and for regulating irrigation deficit for enhancing and improving the crop yield (Samjstrla and Harrison, 1998). These studies indicate fundamental properties of the soil are dependent on Ψ (Gourley and Schreiner, 1995). Although many suction measurement devices (Lee and Wray, 1995), which avoid the need for constant measurements (Woodburn and Lucas, 1995) are available these days, a field tensiometer has been found to be quite efficient for measuring the soil suction within a range of 0-100 kPa (Stannard, 1992; Sneha, 2001). Ψ when plotted against the gravimetric moisture content yields a soil-water characteristic curve (SWCC) (Fredlund and Xing, 1994). Integration along the SWCC provides the quantity of water in the soil, which in turn can be used to estimate the unsaturated soil hydraulic conductivity, indirectly (Fredlund et al., 1994).

An attempt is made in the present study to develop the SWCC for locally available silty soil with the help of a field tensiometer. The obtained

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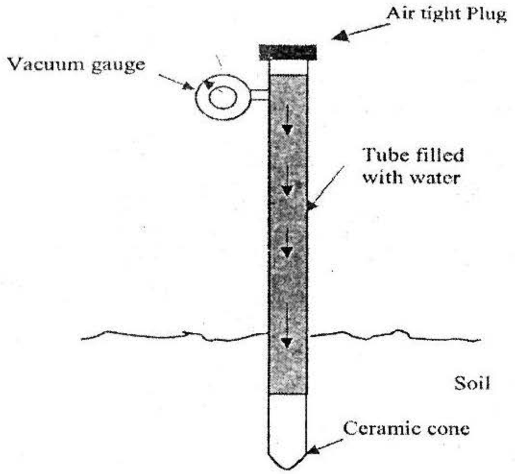

FIGURE 1 : Schematic Diagram of the Tensiometer Used in the Study

SWCC has been compared with the trends obtained from various pedotransfer functions, PTFs, available in SoilVision 2.4. The paper also demonstrates estimation of the unsaturated soil hydraulic conductivity using the obtained SWCC, over a wide range of suction.

Experimental Investigations

A field tensiometer, as detailed in Fig.1, and with its properties listed in Table 1, was used to measure Ψ in the soil. When the tensiometer is inserted in the soil, the ceramic cone transports water via capillary action

TABLE 1 : Details of the Tensiometer Used in the Study

Tensiometer tube:	
Material	PVC
Length (mm)	820
Diameter (mm)	10
Cone:	
Material	Ceramic
Length of the cone (mm)	80
Insertion depth (mm)	100
Suction measurement range	0-100 kPa

from its interior to the exterior, creating a partial vacuum in the tensiometer tube. This partial vacuum is composed of the soil suction, Ψ, and the height of water in the tensiometer tube, h_w, and is a measure of moisture in the soil (i.e. saturation of the soil mass). The flow of water from the tensiometer tube into the soil through the ceramic cup continues until an equilibrium is reached between the energy of water in the tensiometer and that in the soil mass. The tensiometer is equipped with a vacuum gauge, as shown in Fig.1, which measures the soil suction, Ψ, directly. Proper contact between the soil mass and the tensiometer cone was ensured for proper functioning of the tensiometer. As the column of water inside the tensiometer affects the tensiometer measurements, suitable correction (as per Eqn.1) is applied to its readings, Ψ:

$$\Psi_T = \left(\Psi - h_w\right) \tag{1}$$

In Eqn.1, h_w can be determined by measuring the height of the water column and converting it to an equivalent pressure (a 10 cm water column would exert a pressure of 1 kPa). This correction was applied prior to analysing the tensiometer readings.

Test Set-up

A sample of locally available silty soil was used in the present study. The soil sample was characterized as per ASTM D 422-63 (1994), ASTM D 698-91 (1994) and ASTM D 854-92 (1994) and its properties are listed in Table 2.

The soil was compacted in a stainless steel mould (internal diameter 150 mm and height 175 mm) to a dry unit weight, γ_d, of 14.6 kN/m^3 with different moisture contents, w. To ensure a proper contact of the tensiometer with the soil, a coring tube (diameter 33 mm) slightly less than the diameter of the cone of the tensiometer, was used to create a hole, which is long enough to accommodate the tensiometer cone. To ensure proper functioning of the tensiometer, the tensiometer tube was filled with de-aerated water (prepared by boiling water and then cooling it) and soaking the tensiometer cone in this water for at least 24 h, prior to starting the experiment.

Results and Discussion

The variation of measured suction, Ψ, with time for the soil with γ_d equal to 14.6 kN/m^3 and with different saturation, S_r, is depicted in Fig. 2. The trends depicted in the figure indicate that for the soil sample with lesser S_r, the initial portion of the measured suction vs. time response is very steep. However, in general the suction values do not exhibit any rapid change over

TABLE 2 : Properties of the Silty Soil Used in the Study

Soil Property	Silty soil
Specific gravity	2.79
Particle size characteristics:	
Sand (%):	
Coarse (4.75-2.0 mm)	3.7
Medium (2.0-0.420 mm)	17.7
Fine (0.420-0.074 mm)	27.8
Fines (%):	
Silt size (0.074-0.002 mm)	35.9
Clay size (< 0.002 mm)	14.9
Consistency limits (%):	
Liquid limit	41
Plastic limit	28
Plasticity index	13
Soil Classification (USCS)	ML
Standard Proctor compaction	γ_{dmax} = 17.05 kN/m^3 O.M.C. = 20.5% S_r at O.M.C. = 91.2%

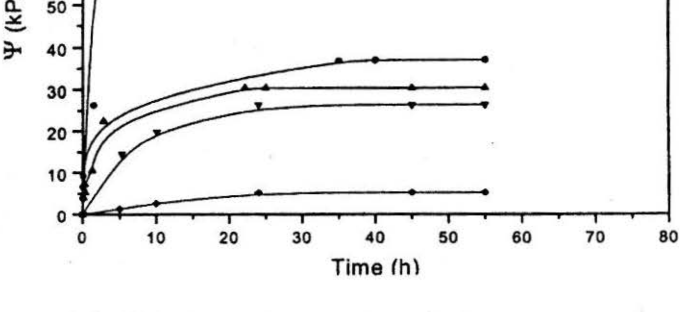

FIGURE 2 : Variation of Soil Suction with Time

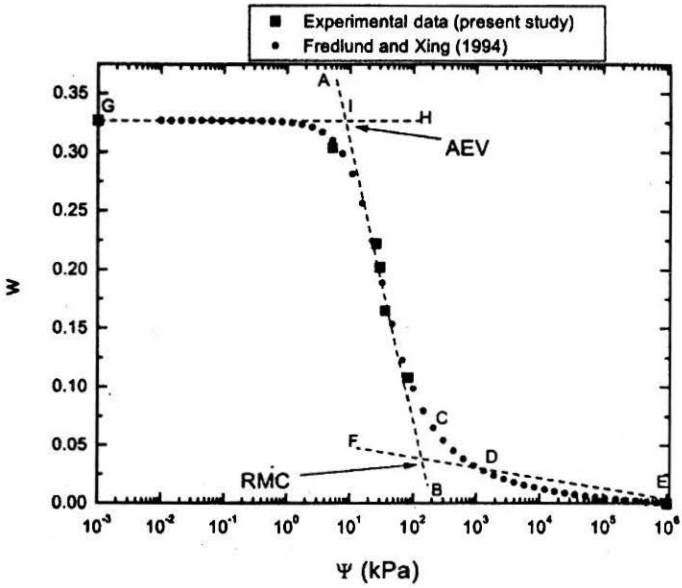

FIGURE 3 : Experimentally Determined SWCC for the Soil Sample

a long duration of time and by 55 to 60 h, an equilibrium value of Ψ is achieved. However, due to the limitations of the tensiometer, only $\Psi < 100\,\mathrm{kPa}$ could only be measured. Based on extensive studies and experimentation, researchers have proposed various equations to describe the soil-water characteristic curves for soils. One of the most popular and commonly used equations is the equation proposed by Fredlund and Xing (1994). This equation has the flexibility to fit a wide range of soils and provides very high accuracy especially in the high suction range. As experimentally obtained SWCC lacked data in the high suction range, Fredlund and Xing equation was fitted to the experimental data, using SoilVision 2.4, as depicted in Fig. 3. This enabled estimation of the SWCC for the soil over a wider range of Ψ. The Fredlund and Xing equation can be written in the following form:

$$\left(\frac{w}{w_s}\right) = \left[1-\frac{\ln\left[1+\frac{\Psi}{h_r}\right]}{\ln\left[1+\frac{10^6}{h_r}\right]}\right] * \left[\frac{1}{\left[\ln\left[\exp(1)+\left(\frac{\Psi}{a_f}\right)^{n_f}\right]\right]^{m_f}}\right] \tag{2}$$

where w = water content at any suction, Ψ,

w_s = water content at saturation,

a_f = soil parameter which is a function of air entry value,

n_f = soil parameter which is a function of rate of extraction of water from the soil beyond the air entry value, AEV,

m_f = soil parameter which is a function of the residual moisture content, RMC,

h_r = suction corresponding to RMC.

Based on the SWCC obtained from the experimental data (Fig.3) and by fitting Fredlund and Xing equation to it, attempts were made to determine AEV, the suction value at which the largest pores in the soil start draining, and RMC, the moisture content at which the water phase in the soil becomes largely discontinuous, by adopting the following geometrical construction (Fredlund and Xing, 1994):

1) The point of maximum slope on the best-fit curve is located and a tangent (AB) to the curve at this point is drawn.

2) The point of inflexion, C, (i.e., the point of maximum change of slope) between the point of maximum slope and 10^6 kPa is determined.

3) Moving about one logarithmic cycle past the point C, on the best-fit curve, a point D is located. A line (ED) is drawn through D and 10^6 kPa.

4) The intersection of the ED and AB yields the RMC of the soil.

5) A horizontal line (GH) is drawn through the point of maximum moisture content.

6) The intersection of GH and AB (i.e., Point I) yields the AEV.

Based on this construction, the RMC and AEV are found to be 4% and 8.0 kPa, respectively. However, to generalize the results obtained, the knowledge-based database SoilVision 2.4 has been employed to develop SWCC curves for the soil, as depicted in Fig.4, and to estimate RMC and AEV values, using different fit equations, as shown in Table 3. For the soil sample, the value of saturation moisture content, ws, is taken as 32.65% (Singh and Gupta, 2000). SoilVision 2.4 employs the concept that for a particular soil, its SWCC depends on its particle size distribution (Fredlund

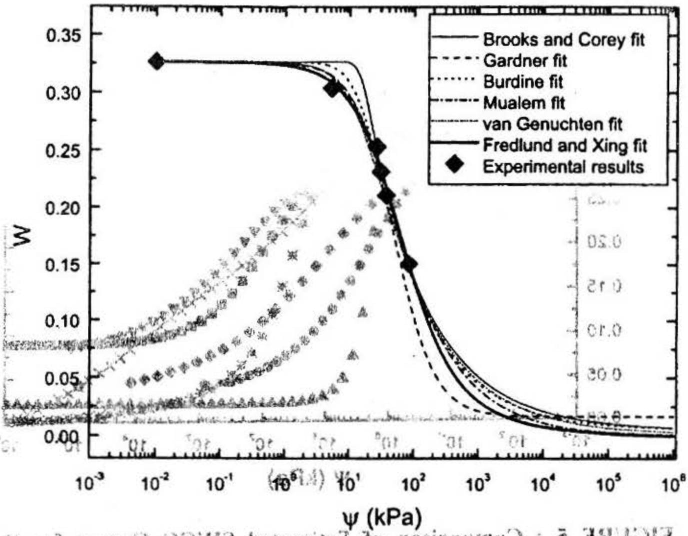

FIGURE 4 : Validation of Experimentally Obtained SWCC for the Soil Sample

TABLE 3 : Comparison of SWCCs Obtained by Using SoilVision 2.4

Fit Equation and PTF	AEV (kPa)	RMC	
		Criterion	(%)
Fredlund and Xing	8.00	From Fig. 3	4.00
Brooks and Corey	13.39	0.85% of w_s	0.30
Van Genuchten	5.44	0.51% of w_s	0.017
Mualem	7.88	0.0% of w_s	–
Burdine	–	0.33% of w_s	0.11
Gardner	0.73	0.60% of w_s	0.19
Arya and Paris	0.29	–	–
Scheinost	4.66	–	0.08
Rawls	1.20	–	–
Vereecken	6.43	–	0.09
Tyler	0.18	–	–
Fredlund and Wilson	1.82	–	–

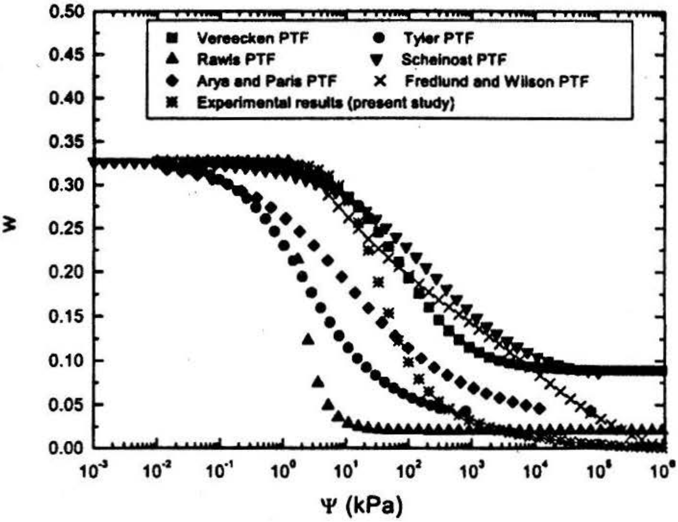

FIGURE 5 : Comparison of Estimated SWCC Curves for the Soil Sample

and Xing, 1994). As such, an attempt has been made to determine SWCC for the silty soil, used in the present study, based on its particle size distribution. The results obtained using different pedo-transfer functions (PTFs) available in SoilVision 2.4 have been compared with the experimentally obtained results. Details of this study are depicted in Fig.5 and Table 3. It can be noticed from the data presented in Table 3 that the AEV values obtained from different fits as well as PTFs bracket the AEV value obtained for the soil sample with the help of field tensiometer. However, RMC values cannot be compared due to difference in philosophies proposed by various researchers. It can be observed form Fig.5 that the experimentally observed SWCC fitted to the Fredlund and Xing equation lies within the band of SWCC curves predicted using the various PTFs available in SoilVision 2.4. This study indicates usefulness of a field tensiometer for measuring suction in the soil mass.

Estimation of Soil Hydraulic Conductivity

The SWCC for the silty soil has been used to obtain the unsaturated soil hydraulic conductivity, k, using SoilVision 2.4 and linking it to the saturated soil hydraulic conductivity, k_{sat}, obtained by using the following equations:

1) As per Rawls and Brackensiek (1985), the ksat (m/s) can be expressed as:

$$k_{sat} = \left[\exp\begin{pmatrix} 19.52348 * n - 8.96847 - 0.028212 * C \\ + 0.00018107 * S^2 - 0.0094125 * C^2 \\ - 8.395215 * n^2 + 0.077718 * S * n \\ - 0.00298 * S^2 * n^2 \; - 0.019492 * C^2 * n^2 \\ + 0.0000173 * S^2 * C + 0.02733 * C^2 * n \\ + 0.001434 * S^2 * n - 0.000035 * C^2 * S \end{pmatrix} * 2.77 * 10^{-6} \right] \qquad \text{..........} (3)$$

for the soils satisfying the following constraints:

$$5 < S < 70 \quad \text{and} \quad 5 < C < 60$$

where S and C are the sand and clay fractions are as per the USDA classification and n is the soil porosity.

2) As per Rawls et al. (1992), the ksat (m/s) can be expressed as:

$$k_{sat} = 4.41 \times 10^7 \left[\frac{n^x}{N^2} \right] R_1^2 \qquad (4)$$

where n = soil porosity,

x = soil dependent constant,

N = total pore size classes and

R_1 = average pore radius (cm).

For the soil under consideration, Eqns.3 and 4 yield k_{sat} equal to 5.80E−07 m/s and 3.50E−07 m/s, respectively. Using an average k_{sat} equal to 4.65E−07 m/s and Fredlund and Xing PTF, the variation of k_r, the relative hydraulic conductivity, which is defined as the ratio of unsaturated soil hydraulic conductivity to the k_{sat}, with soil suction, Ψ, is plotted as shown in Fig.6.

The study demonstrates application of a field tensiometer in establishing the SWCC for a particular soil and estimating its unsaturated hydraulic conductivity.

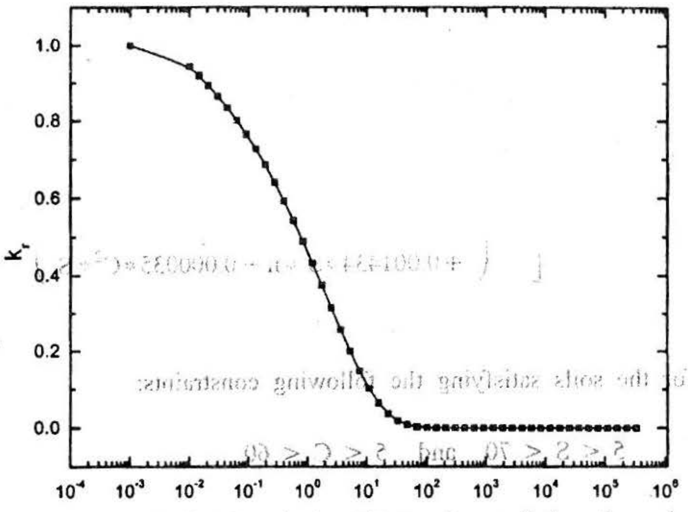

FIGURE 6 : Variation of Relative Hydraulic Conductivity of the Soil with Suction

Concluding Remarks

Utility of a field tensiometer in measuring soil suction (< 100 kPa) has been demonstrated in the present study. Using the soil suction, the soil–water characteristic curve, SWCC, for a soil has been developed. Comparison of the obtained SWCC with those predicted by using different pedo-transfer functions, PTFs, available in the literature indicates an excellent matching. The study also demonstrates application of the SWCC in estimating the unsaturated soil hydraulic conductivity. However, for accurate estimation of the SWCC, and hence the unsaturated hydraulic conductivity of the soil, sophisticated instruments (such as a pressure plate apparatus, a dew point potentiameter, psychrometers), which are capable of measuring suction over a wide range, must be employed.

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Notations

γ_d = dry unit weight;

γ_{dmax} = maximum dry unit weight;

AEV = air entry value;

a_f = soil parameter, which is a function of air entry value;

C = clay fraction as per USDA classification;

h_r = suction corresponding to RMC;

k = unsaturated soil hydraulic conductivity;

k_r = relative hydraulic conductivity;

k_{sat} = saturated soil hydraulic conductivity;

m_f = soil parameter, which is a function of RMC;

n = soil porosity;

N = total pore size classes;

n_f = soil parameter, which is a function of rate of extraction of water from the soil beyond the AEV;

O.M.C. = optimum moisture content;

PTF = pedo-transfer function;

R_1 = average pore radius;

RMC = residual moisture content;

S = sand fraction as per USDA classification;

S_r = degree of saturation;

Ψ = soil suction;

w = gravimetric moisture content;

w_s = saturation moisture content;

h_w = height of water in tensiometer tube;

x = a soil dependent constant.