Suction–Water Content Relationship for Hill Soil of North-East India

C. Malaya and S. Sreedeep

Abstract Hill-slopes of north-east (NE) India mainly constitute of unsaturated red soil. While analyzing the stability of hill-slope, hydrology, i.e., infiltration and surface drainage becomes indispensable. Defining this suction–water content relationship (SWR) of the soil is important. It is generally expressed in terms of a graphical relationship between soil suction and water content (or saturation). SWR of red soil has been obtained using equitensiometer, relative humidity sensor, and volumetric water content sensor. From the measured SWR, its parameters were defined. The parameters defining this SWR are key input for analyzing hill-slope hydrology and stability. The details of the methodology adopted in this study are presented in this paper.

Keywords Hill-slope · Unsaturated soil · Suction–water content relationship · Parameters · Hydrology · Stability

1 Introduction

The hill-slopes of north-east (NE) India consist of unsaturated red soil (RS). In NE India, hill-slope developmental activities have increased the occurrence of landslides during the rainy season due to the heavy rainwater infiltration and surface drainage. Accurate description of infiltration and surface drainage for unsaturated soil remains a fundamental problem in hydrology. Modeling of rainfall infiltration and surface drainage is needed for the analysis of slope failure induced by heavy rainfall (Chen and Lee 2003). The parameters of soil suction–water content relationship (SWR) are crucial inputs for this. SWR is defined as the relationship

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between soil suction and water content (either, gravimetric or volumetric) or soil saturation (Fredlund and Rahardjo 1993).

This study deals with the measurement of the SWR of RS with the help an equitensiometer (EQT) and a relative humidity sensor (RHS). SWR equations reported in the literature Fredlund and Rahardjo (1993) are fitted to the measured SWR for RS for determining its SWR parameters.

1.1 Theoretical Background

Soil specific parameters for a typical drying (desorption) SWR are: (1) the volumetric water content at saturation, θ_s, which is the water content at which the soil is completely saturated and typically depicts the initial condition for the drying path, (2) air entry value (AEV), which is defined as the suction at which air starts entering the largest pores present in the soil sample, and (3) residual water content (θ_r), defined as the water content below which water content changes are minimal as suction changes.

In this study, the SWR is represented by van Genuchten (1980) and Fredlund and Xing (1994) equation represented by Eqs. 1 and 2, respectively

$$\theta(\psi) = \theta_r + (\theta_r - \theta_s)\left[\left[1 + \left(\frac{\psi}{a_{vg}}\right)^{n_{vg}}\right]^{m_{vg}}\right]^{-1} \tag{1}$$

$$\theta(\psi) = \theta_s\left[1 - \frac{\ln\left[1 + \frac{\psi}{h_r}\right]}{\ln\left[1 + \frac{10^6}{h_r}\right]}\right]\left[\left[\ln\left[\exp(1) + \left(\frac{\psi}{a_f}\right)^{n_f}\right]\right]^{m_f}\right]^{-1} \tag{2}$$

where $\theta(\psi)$ is the volumetric water content at any suction, ψ; θ_r is the residual volumetric water content; θ_s is the volumetric water content at saturation; a_{vg} and a_f are fitting parameters primarily dependent on the air entry value (AEV); n_{vg} and n_f are fitting parameters that are dependent on the rate of extraction of water from the soil; m_{vg} and m_f are fitting parameters which depend on θ_r; h_r is the suction (in kPa) corresponding to residual state.

The computer code RETC, version 6.02 (Van Genuchten et al. 1991) has been used for estimation of SWR parameters. RETC uses nonlinear least-squares optimization technique for curve fitting.

2 Materials and Methods

A locally available fine-grained red soil from hill-slope designated as RS was used in this study. The soil is characterized for its specific gravity, grain size distribution, liquid limit, and plastic limit by following the guidelines presented in the literature

Table 1 Physical properties and classification of the soil used in the study

Property	Soil RS
Specific gravity	2.62
Particle size characteristics (%)	
Sand (4.75–0.075 mm)	26
Coarse sand (4.75–2 mm)	0
Medium sand (2–0.425 mm)	5
Fine sand (0.425–0.075 mm)	21
Silt (0.075–0.002 mm)	67
Clay (<0.002 mm)	7
Atterberg limits (%)	
w_L	46
w_P	27
I_P	19
Classification*	CL

*ASTM 2008

(ASTM 2005a, 2006, 2007). The details of the characterization are listed in Table 1. It can be noted that the soil is clayey soil of low compressibility.

The equitensiometer (EQT) consists of a precision soil moisture sensor, the ThetaProbe, whose measuring rods are embedded in a porous material, the equilibrium body. The porous material has a known, stable relationship between water content and matric suction (ψ_m). When the (EQT) is inserted into the soil for matric suction (ψ_m) measurement, it equilibrates with the surrounding soil. The water content of the equilibrium body is measured directly by the ThetaProbe and gives the output in millivolt (mV) (Soil Matric Potential Sensor, User Manual 1999), and this is converted to ψ_m of the surrounding soil using the calibration curve supplied by the manufacturer (Delta-T Devices, UK).

The EC-TE volumetric water content sensor (VWCS) is low cost sensor manufactured by Decagon Inc. USA. This probe determines 'θ' based on the dielectric constant or permittivity of the material in which it is inserted. EC-TE is a three-pronged probe. The details of this probe are reported in the literature (Kizito et al. 2008; Malaya and Sreedeep 2010). The measurements using equitensiometer and EC-TE probes are performed employing the test set up as shown in Fig. 1. The test set up essentially consists of a perspex container with a base plate into which the soil is compacted. The ψ_m and θ measuring probes are connected to a computer through respective data loggers.

The air-dried soil is compacted at required compaction state in the perspex mold of 200 mm diameter and 160 mm height. The EC-TE probe is inserted directly into the soil, and the sharpened tip of the probe facilitates the insertion process. For inserting equitensiometer, dummy hole is made (whose size is smaller than the probe size) and then the probe is inserted. It must be noted that the soil next to the probe has the strongest influence on the readings, and hence sufficient care has been

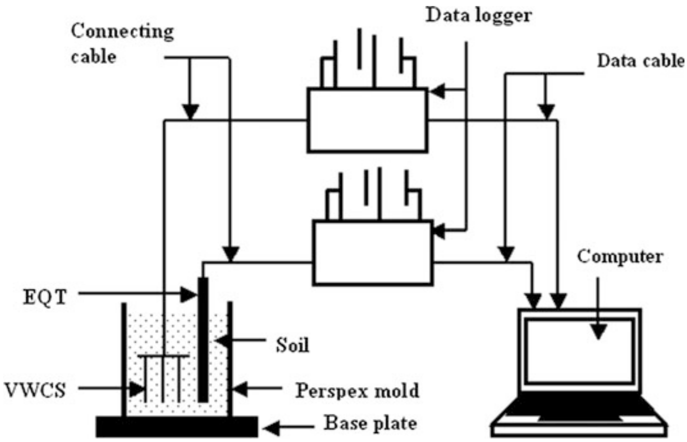

Fig. 1 Details of the EQT test set up used in the study

taken to avoid air gap around the probe. The soil has been initially saturated so that $\psi_m \approx 0$. The probes are inserted into the soil sample and the readings recorded over a period of time. The measured ψ_m and θ values are used for developing SWR.

The RHS essentially consists of two parts: (a) polymer capacitance sensor, which measures relative humidity (0–100 %) and temperature (−40 to 85 °C); and (b) wire filter, which protects the sensor from air-borne particles. The body of the RHS immediately above the polymer sensor is filled with a special resin to quickly remove condensation after measuring high RH samples (Hygroclip Manual 2011). Such a provision reduces the time interval between two successive measurements considerably, as the RHS regains ambient RH rapidly. The connecting cable of the RHS is attached to the read out unit for measurement of RH and temperature. After placing the soil sample in the relative humidity box (RHB), the RH and temperature readings are noted down at regular interval (generally every 5 min) until constant equilibrium value is obtained. In most of the cases, equilibrium was achieved within 40 min of the start of the measurement. The RH and temperature measured at equilibrium are used for determining total suction (ψ) of the soil sample using Eq. 3.

$$\psi = -\frac{R.T}{\upsilon_{w0}.\omega_v}\ln\left(\frac{\bar{u}_v}{\bar{u}_{v0}}\right) \tag{3}$$

where

ψ soil suction or total suction (kPa)
R universal (molar) gas constant [i.e., 8.31432 J/(mol K)]
T absolute temperature in Kelvin [i.e., T = (273 + t_0) (K)]
t_0 temperature (°C)
v_{w0} specific volume of water or the inverse of the density of water [i.e., 1/ρ_w (m^3/kg)]
ρ_w density of water (i.e., 998 kg/m^3 at t_0 = 20 °C)

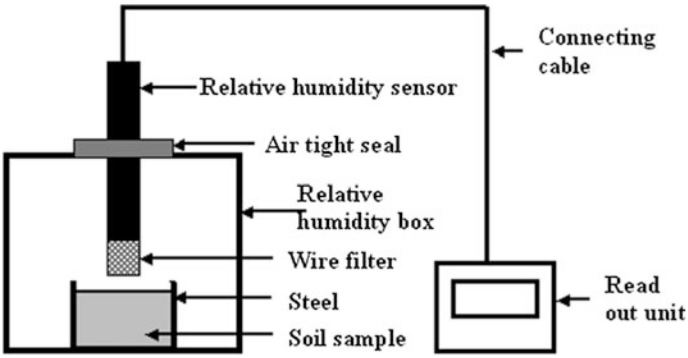

Fig. 2 Details of the RHS test set up used in the study

ω_v molecular mass of water vapor (i.e., 18.016 kg/kmol)
$\bar{u}_v$ partial pressure of pore-water vapor (kPa)
$\bar{u}_{v0}$ saturation pressure of water vapor over a flat surface of pure water at the same temperature (kPa)

The term $\bar{u}_v/\bar{u}_{v0}$ is called relative humidity, RH (in %). Depending upon the purity of pore water, $\bar{u}_v$ will change. Since there are no salts present in the soil used in this study, Eq. 3 will give $\psi = \psi_m$.

The relative humidity test set up employed for the present study is depicted in Fig. 2. A sharp edged stainless steel ring of internal diameter less than the unconfined compressive strength sample maker and height 15 mm has been used to extract compacted soil sample. The steel ring with compacted soil sample is placed in an in-house fabricated Teflon relative humidity box (RHB), which is perfectly airtight. The RHB is 65 mm in internal diameter and 60 mm in height. The top cap of the RHB is fitted with HygroClip S (ROTRONIC AG, Grindelstrasse 6) relative humidity sensor (RHS) (as shown in Fig. 2) in such a way that its tip (sensing portion) remains just above the top surface of the soil sample. The ψ measurements were conducted on “as compacted” soil samples. The water content, w of compacted soil sample has been determined by following the guidelines presented in ASTM 2005b. The measured ψ and θ values are used for developing SWR.

3 Results and Discussion

The ψ_m and θ values obtained using EQT and VWCS are plotted as depicted in Fig. 3.

The ψ (=ψ_m) values measured using RHS are plotted as shown in Fig. 4. θ was computed corresponding to ψ measurements from the measured w and dry unit weight of the soil sample. The entire data obtained from EQT and RHS measurements were used to plot SWR of RS as depicted in Fig. 5. The combined data

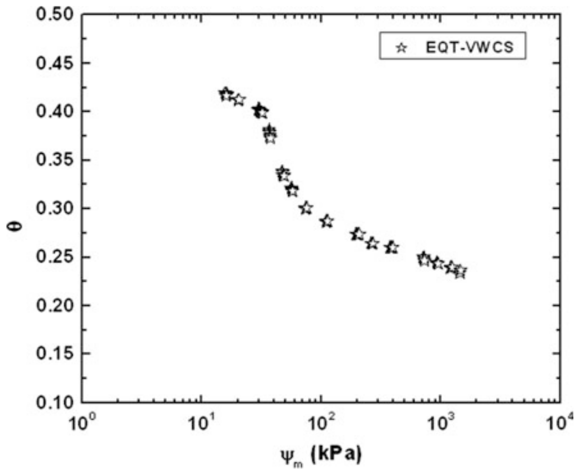

Fig. 3 SWR obtained from EQT measurement for RS

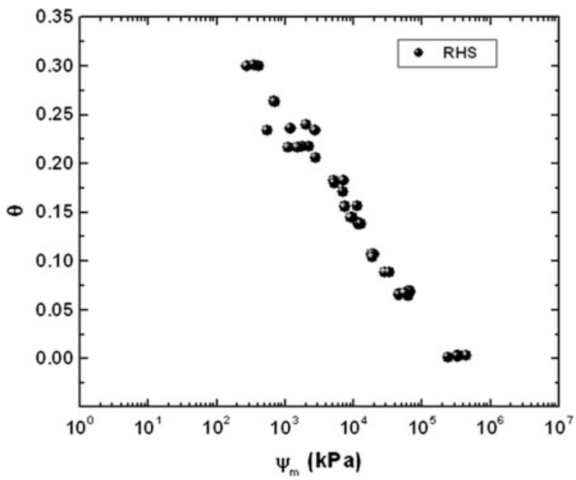

Fig. 4 SWR obtained from EQT measurement for RS

points bridge together well for soil RS to give a broad range of measured ψ_m. The combined SWRs of RS were used for obtaining SWR parameters. SWR Eqs. 1 and 2, designated as VG and FX, respectively, have been fitted to the experimental data using the computer code RETC. The SWR equation parameters obtained from this analysis are listed in Table 2. It can be observed that the fitting functions yield a regression coefficient (R^2) close to unity, which indicates an excellent fit to the experimentally obtained data.

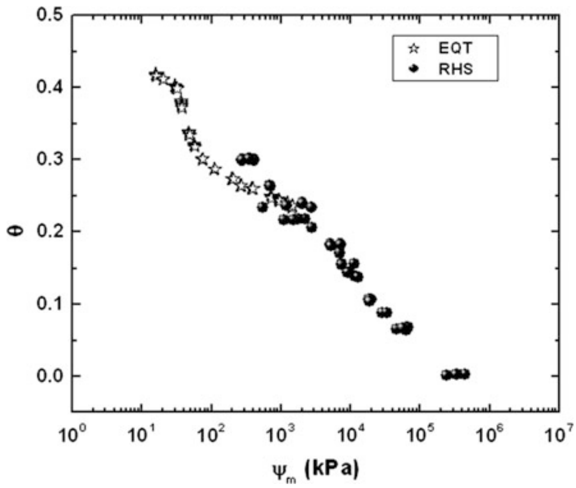

Fig. 5 Combined SWR obtained from EQT and RHS measurement for RS

Table 2 Details of the SWR equation fitting parameters for RS

Fitting function	Parameter	Value
VG	a_{vg} (kPa)	16.44
	n_{vg}	13.38
	m_{vg}	0.0114
	θ_r	0
	θ_s	0.4167
	R^2	0.9310
FX	a_f (kPa)	31.10
	n_f	14.64
	m_f	0.1135
	h_f (kPa)	819.92
	θ_s	0.4167
	R^2	0.9856

4 Conclusion

The study deals with the measurement and parameterization of SWR of a locally available red soil from a hill-slope. The SWR was measured using EQT and RHS. The SWR parameters of van Genuchten and, Fredlund and Xing models were obtained by fitting the SWR equations to the experimental data using computer code RETC, version 6.02. The SWR parameters are important inputs for modeling rainwater infiltration and surface drainage in hill-slopes for the analysis of slope failure induced by heavy rainfall.

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