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Estimating Hydraulic Properties of Unsaturated Soil Using a Single Tensiometer

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Abstract

Determination of the hydraulic properties of unsaturated soils is essential for the modeling of water flow and solutes transport. Methods of measuring these parameters are often expensive. In this study, a laboratory experiment is presented for the characterization of the hydraulic properties based on the principle of the evaporation method. It is based on following the variation of the water content by the gravimetric method and the pressure head by a tensiometer along a drying cycle of a small sample of soil. The measured retention curves are adjusted on the model of van Genuchten by the RETC software and are then compared with values measured by the pressure chamber method (reference method). The statistical evaluation shows the validity of this simple method for the measurement of the retention curves of unsaturated soils and for the estimation of the hydraulic properties.

Keywords

Unsaturated Soils, Hydraulic Properites, Parameter Optimization, RETC, Soil Retention Curve

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1. Introduction

Water flow and solute transport modelling in the unsaturated soils the estimation of the hydraulic properties. In situ field measurements of soil retention properties are tedious, costly, time consuming and are not accurate because of experiment shortcoming and high spatial and temporal variability. Therefore, the retention properties of unsaturated soils are often estimated indirectly from other soil properties using pedotransfer functions (PTFs) ([1]; [2]; [3]; [4]) or determined in the laboratory ([5]; [6]; [7]; [8]), which allow higher spatial and temporal resolution. Among the most widely used and easily methods to determine the retention curve and hydraulic conductivity of unsaturated soils is the evaporation method. This method is based on measuring both soil moisture and pressure head during a soil drying cycle under the only effect of evaporation. It was developed by [9] which introduced an iterative graphical procedure to estimate, firstly, the water retention curve from average soil moisture and pressure head readings, and then determined hydraulic conductivities from measured pressure head profile and variations in water content distribution. In general, five tensiometers, in a measuring range from -50 cm to -700 cm, are used in evaporation methods, several authors have proposed to reduce the number of tensiometers to 2 ([10]; [11]; [12]). [13], [14] and [15] have used only one tensiometer in small soil cores and showed that this method is able accurately to estimate soil hydraulic characteristics. Furthermore, as an alternative to Wind Algorithm, the analysis of water flow during an evaporation experiment can be performed by using optimization algorithms. RETC software [16], which is based on the Levenberg-Marquardt optimization algorithm is often used for estimating soil hydraulic parameters by fitting analytical models to measured data. Among the most popular closed-form

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analytical expression for hydraulic properties is that of [17], which is able to predict hydraulic conductivity from the retention curve and is more convenient for numerical models of water flow in the unsaturated zone.

The objective of this paper is to estimate soil water retention properties of an unsaturated soil by an evaporation laboratory method. This method is to monitor the water content by the gravimetric method and the pressure head by a tensiometer, during a drying cycle of a small soil container under the effect of evaporation and using the RETC program to estimate the van Genuchten model parameters from measured retention curves.

2. Material and Methods

2.1. Laboratory Experiment

A silty clay soil (Table 1) was sampled from a land parcel (36°50'40.791"N, 10°11'13.795"E in the town of Ariana (Tunisia). The soil sample were crushed and then placed in small clear plastic containers. A tensiometer was implanted in the middle of each soil layer (Figure 1).

Table 1. Soil particle size analysis of the three soils.

	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	Texture (USDA*)
Soil	30	50	20	Silty clay

* Scheme: United States Dept. of Agriculture

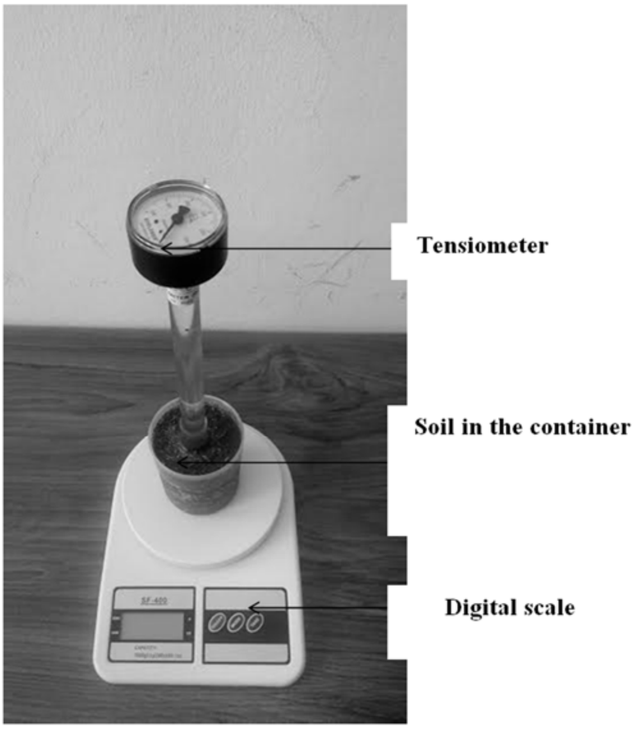

Figure 1. Photo of soil laboratory experiment.

The soil was saturated from the top with distilled water and was left to evaporation. During the drying cycle, no device was used to accelerate evaporation. Monitoring volumetric water content was performed by gravimetric method (weighing scale) and the pressure head by the tensiometer. Upon conversion of gravimetric water content to volumetric humidity, the values of bulk density were measured by the cylinder method. The measurements were made daily until the digital meter indicates h = -600 cm, which corresponds to the sensor limit.

2.2. Parameter Estimation

The analytic model of [17] was used to set the water retention curve $\theta(h)$, which relates the volumetric water θ content in pressure potential h. The equation of van Genuchten (1980) for the retention curve is:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h^n|\right]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad ; \; m = 1 - \frac{1}{n} \qquad n > 1 \quad (1)$$

where θ_r is the residual water content [L^{-3}L^{-3}], θ_s is the saturated water content [L^{-3} L^{-3}], h is the water pressure head [L], α [L^{-1}] and n [-] are shape parameters.

Equation (1) contains up to four independent coefficients, represented by the parameter vector b = {θ_r, θ_s, α, n}. The different parameters are essentially empirical coefficients without much physical significance [18]. Their values were estimated by fitting the retention model to the observed data using the parameter optimisation RETC [16]. This program uses Marquardt's maximum neighbourhood method to minimize the objective function, O(b):

$$\min_b O(b) = \sum_{i=1}^{N} \left[\left(\theta_i - \hat{\theta}_i(b)\right)\right]^2 \qquad (2)$$

where θ_i and $\hat{\theta}_i$ are the observed and fitted water contents, respectively, and N is the number of retention data. Initial values for the soil hydraulic parameters θr, θs, α and n were estimated with the ROSETTA [1] pedotransfer function using measured data of sand, silt, and clay contents (Table 2).

Table 2. Initial values of van Genuchten soil retention parameters estimated by Rosetta.

	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	K_s (cm d^{-1})
Soil	0.0541	0.3727	0.0301	1.587	62.98

2.3. Pressure Chamber

Soil samples were placed in a pressure chamber. The same pressures measured by the tensiometer were applied to soil cores. For each value of pressure (from 0 cm to -600 cm), water content was measured gravimetrically. The pressure chamber (refrence method) was used to validate the values obtained by the proposed laboratory method.

2.4. Statistical Analysis

To evaluate measured retention curves measured by the proposed laboratory method, two statistical parameters were used: the root mean square error (RMSE) and the geometric mean error ratio (GMER). These statistical parameters are calculated as follows:

$$RMSE\left(\%\right) = \sqrt{\frac{\sum_{i=1}^{n}(L_i - P_i)?}{j}} \times \frac{1}{\overline{P}} \times 100 \quad (3)$$

$$GMER = \exp\left[\frac{1}{j}\sum_{i=1}^{j}\ln\left(\frac{Li}{Pi}\right)\right] \quad (4)$$

where L_i are the measured values by laboratory method, P_i are the values measured by pressure chamber, $\overline{P}$ is the average value of pressure chamber data and j is the number of observations. The RMSE and the GMER equal to 0 and to 1, respectively, correspond to an exact match between observed and fitted data. The GMER value less or greater to 1 indicates that the corresponding model underestimates or overestimates fitted data. The smaller (closer to 0) the RMSE value was, the better the model was.

3. Results

During their drying cycle, the pressure head (h) has varied from a saturated state (h = 0 cm) to a completely dry state (h = -600 cm) for all the layers. Measured water retention data obtained from the evaporation experiment were fitted by RETC to estimate the van Genuchten equation parameters (Figure 2).

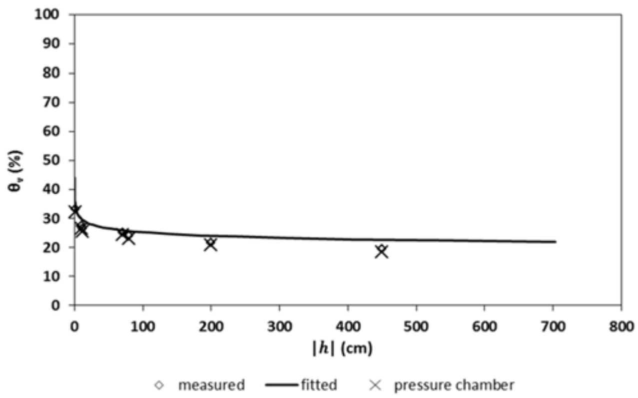

Figure 2. Measured and fitted soil retention curves of Bouhajla unsaturated soils.

Strong correlations were noticed between measured and fitted curves, $r^2 = 0.98$. The values of van Genuchten's equation parameters and the values of the objective function O(b) were assigned in table 3.

Table 3. Estimated van Genuchten soil retention proprieties and values the objective function.

	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	K_s (cm d^{-1})	r^2	O(b)10^{-4}
Soil	0.0100	0.4432	34.9800	1.0783	12.53	0.98	185.30

Good agreement between fitted and measured (by the pressure chamber) retention curves are shown in figure 2. The RMSE (= 8.82 %) and GMER (= 1.28) calculated for the studied soil are close to 0 and 1, respectively. GMER values were greater than 1. The proposed measurement method may slightly overestimate the soil water retention curve.

4. Conclusion and Perspectives

Determination of the hydraulic properties of unsaturated soils by the original evaporation method [9] allows the simultaneous estimation of retention curves and hydraulic conductivity curves. The proposed method proposed in this paper measures the retention curve only and uses the RETC software to estimate the hydraulic conductivity curve. Compared to the laboratory method proposed by [7], the size of the sample is smaller, which means the measured parameters are more significant and the pressure is measured by a conventional tensiometer which is more accurate than the Watermark sensor used by [7]. As a perspective, the Wind algorithm can be used to estimate the hydraulic conductivity curve as well as the use of new optimization algorithms to adjust the measured retention curves.

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