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Laboratory Method for Estimating Water Retention Properties of Unsaturated Soil

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Abstract

Soil hydraulic properties are necessary for modeling water flow and solute transport in the vadose zone. However, direct measurement of these characteristics in field conditions is tedious, time-consuming and expensive. In this study, a laboratory method was used to characterize soil water retention curves of three soil samples in the region of Bouhajla (Central Tunisia). For experimental purposes, volumetric water content and pressure head values were measured using the gravimetric method and Watermark sensor, of a small disturbed soil core, respectively, during a drying cycle under the effect of evaporation. The van Genuchten model was fitted to the measured retention curves with the RETC software to determine residual water content (θ_r), saturated water content (θ_s) and the two shape parameters; α and n. Strong correlations were found between the fitted and measured retention curves. The van Genuchten model was also fitted to the retention curves measured by pressure chamber (as the reference method). The results were evaluated by calculating the root mean square error (RMSE) and the geometric mean error ratio (GMER). Statistical analysis proved the success of the proposed method for estimating van Genuchten soil retention parameters of the studied soils. A Mann-Whitney test performed at the significance level of 0.05 showed no significant difference between the two methods.

Keywords: Evaporation method, parameter optimization, RETC, soil retention curve, Bouhajla

Introduction

Salinization risk assessment of soils and aquifers in arid and semi-arid regions requires knowledge of the evolution of water movement and solute transport in subsurface flow. During the last decades, a large number of numerical models have been developed for the simulation of water flow and solute transport in the unsaturated zone. Nevertheless, their use in field conditions is often limited by the lack of characterization of retention properties. In situ field measurements of soil retention properties are tedious, costly, time consuming and are not accurate because of experimental shortcomings 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] or determined in the laboratory [3,4], which allow higher spatial and temporal resolution. The evaporation method is one of the most widely and easily used methods to determine the retention curve and hydraulic conductivity of unsaturated soils. This method is based on measuring both soil moisture and pressure head during a soil drying cycle under the effect of evaporation. The method developed by Wind [5] introduced an iterative graphical procedure to estimate, firstly, the water retention curve from average soil moisture and pressure head readings, and to determine hydraulic conductivities from measured pressure head profile and variations in water content distribution. Although, in general, five tensiometers were used in measurements ranging from −50 cm to at least −850 cm, in evaporation methods, several authors have proposed to reduce the number of tensiometers to 2 [6-8]. However, Wessolek *et al.* [9] and Simunek *et al*. [10] have used only one tensiometer in small soil cores and showed that this method is able to accurately estimate soil hydraulic characteristics. Furthermore, as an alternative to the Wind Algorithm, the analysis of water flow during an evaporation experiment can be performed by using optimization algorithms. The RETC software [11] which is based on the Levenberg-Marquardt optimization algorithm is often used for estimating soil hydraulic parameters by fitting water retention and hydraulic conductivity models to measured data.

The overall objective of our study is the numerical simulation of water movement and salts transfer in Bouhajla (Central Tunisia), characterized by saline soils [12], to try to assess groundwater contamination risk. The specific objective of this paper is to estimate soil water retention properties of three soils from Bouhajla by an evaporation laboratory method. This method is to monitor the water content by the gravimetric method and the pressure head by a Watermark sensor which allows a wider measurement range than the conventional tensiometer (0 cm to −1,990 cm [13,14], during a drying cycle of a small soil container under the effect of evaporation and using the RETC program to determine the van Genuchten model parameters from measured retention curves.

Material and methods

Laboratory experiment

Three soils presented in **Table 1** were sampled from a land parcel (35°15’47.58’’N; 10°4’17.16’’E) in the village of Bouhajla (Central Tunisia). The soil samples were crushed and then placed in small clear plastic containers (6 cm diameter / 12 cm long). A Watermark sensor (Irrometer Inc., USA) was implanted in the middle of each soil layer (**Figure 1**).

Table 1 Soil particle size analysis of the three soils.

Soil	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	Texture (USDA*)
1	9.5	4.5	85	Sand
2	12.5	30	57	Loam
3	35	5	60	Clay

* Scheme: United States Department of Agriculture

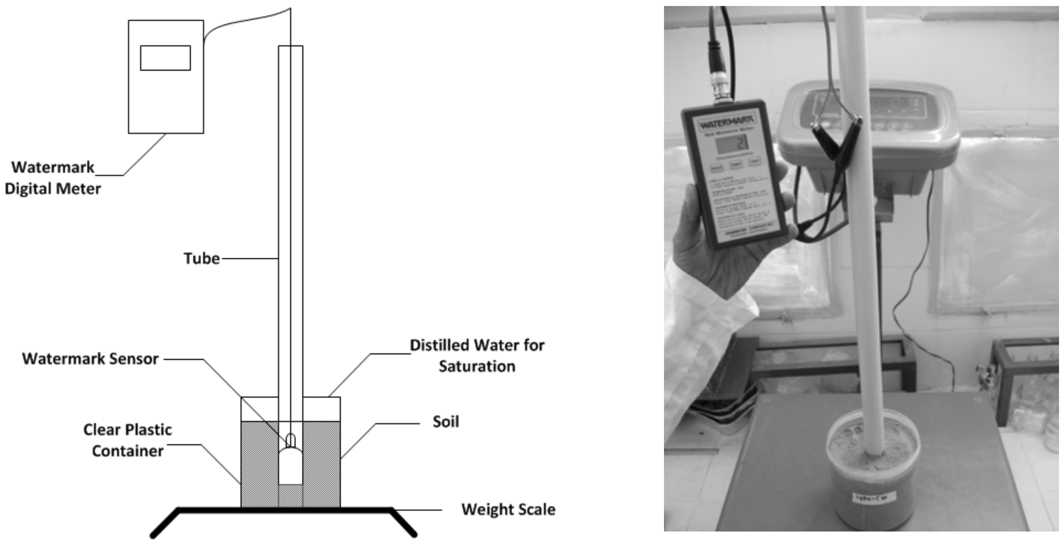

Figure 1 Schematic and photo of soil laboratory experiment.

Each soil was saturated from the top with distilled water and was left to evaporate. During the drying cycle, no device was used to accelerate evaporation. Monitoring volumetric water content was performed by a gravimetric method (weighing scale) and the pressure head by a dielectric method (Watermark sensor). Upon conversion of gravimetric water content to volumetric humidity, the values of bulk density were measured using the cylinder method [15]. The measurements were made daily until the digital meter indicated h = −1,990 cm which corresponds to the Watermark sensor limit.

Parameter estimation

The van Genuchten model [16] was used to set the water retention curve $\theta(h)$, which relates the volumetric water θ [$L^{-3}L^{-3}$] content to pressure potential h [L]. This function is

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

$$m = 1 - \frac{1}{n}, n > 1 \qquad (1)$$

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.

Eq. (1) contains four independent coefficients, represented by the vector b = {θ_r, θ_s, α, n}. The different parameters are essentially empirical coefficients without much physical significance [17]. Their values were determined by fitting the retention model to the observed data using the parameter optimisation RETC software [11]. This program uses Marquardt's maximum neighbourhood method to minimize the objective function, *O(b)*:

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

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 θ_r, θ_s, α and n were estimated with the ROSETTA [18] pedotransfer function using measured values of sand, silt, and clay content (**Table 1** and **2**).

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

Soil	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)
1	0.0547	0.372	0.0298	1.8898
2	0.0466	0.3870	0.0213	1.4091
3	0.0762	0.3859	0.0272	0.0272

Pressure chamber

Soil samples were placed in a pressure chamber. The same pressures measured by Watermark sensors were applied to soil cores. For each value of pressure (from 0 cm to −1,990 cm), water content was measured gravimetrically. The mass of soil sample was determined by subtracting the mass of the container and the probe from total weight. The pressure chamber (reference method) was used to validate the values obtained by the proposed laboratory method. Soils samples were left 48 h in the pressure chamber. Pressure was changed successively on the same sample each 48 h.

Statistical analysis

To evaluate 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:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{j}(L_i - P_i)^2}{j}} \quad (3)$$

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

where L_i is the value measured by the laboratory method, P_i is the value measured by the pressure chamber, $\overline{P}$ is the average value of pressure chamber data and j is the number of observations. The RMSE and the GMER when equal to 0 and 1, respectively, correspond to an exact match between observed and fitted data. The GMER value less or greater than 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.

Statistical processing was achieved by the STATISTICA software, Version 5 (Statsoft France, 1997). The non-parametric Mann-Whitney test was also performed at the significance level of 0.05 (test is significant at $p < 0.05$) to find out whether there is a significant difference between the proposed method and the pressure chamber method or not.

Results

During the drying cycle, the pressure head (h) reduced from a saturated point (h = 0 cm) to a partially saturated point (h = –1,990 cm) for all the soils. However, the values of volumetric water content (θ_v) at the saturation and at the dry end are different between the soils. Sandy soil has the lowest values of θ_v at saturation and at the end of drying than other soil samples. Soil water retention increased with soil enrichment by fine particles (clay + silt). Soil water retention curves of clay soil showed the higher values of θ_v at saturation and at drying and dry while loamy soil showed an intermediate moisture state between them and the surface layer.

Measured water retention data obtained from the laboratory method were fitted by RETC software to determine the van Genuchten equation parameters (**Figure 2**). Strong correlations were found between the measured and fitted curves, the correlation coefficient R^2 ranged between 0.87 and 0.97. The values of van Genuchten’s equation parameters and the values of the objective function *O(b)* are presented in **Table 3**.

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

Soil	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (-)	r^2	$O(b)10^{-4}$
1	0.01678	0.25305	0.0104	2.62368	0.97	38.20
2	0.0093	0.39429	0.00854	1.71022	0.87	69.90
3	0.20436	0.41129	0.03364	2.40498	0.98	185.30

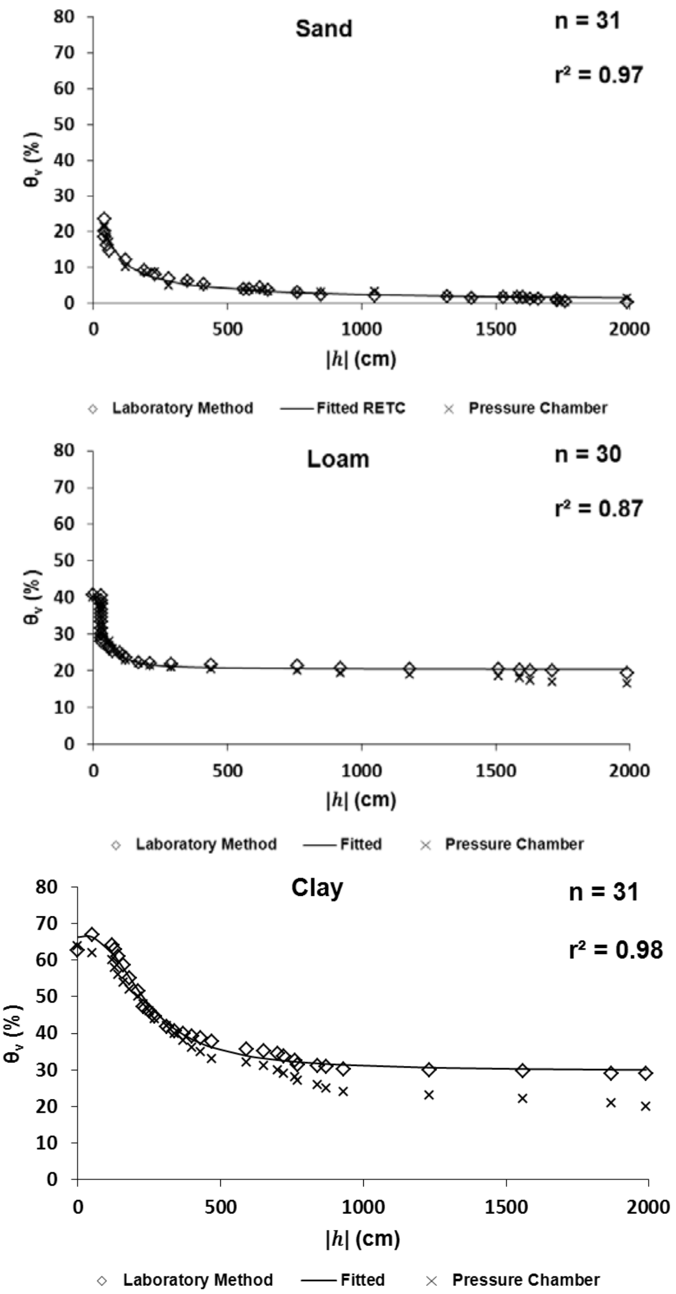

Figure 2 Measured and fitted soil retention curves of Bouhajla unsaturated soils.

The values of these parameters (θ_r, θ_s, α and n) are very heterogeneous between the different soils. Soils 1 and 3 have the highest values of n and α, the most sensitive parameters to water flow [19]. These layers may be particular areas for water movement and solute transport in the unsaturated zone of Bouhajla.

Good agreement between the fitted and measured (by the pressure chamber) retention curves are shown in **Figure 2**. The RMSE and

GMER calculated for the different soil samples are close to 0 and 1, respectively, as shown in **Table 4**. The GMER values were greater than 1 meaning that the proposed laboratory method may slightly overestimate the soil water retention curve. Calculated values of the Mann-Whitney test of the three soils: sand, silt and clay were, respectively, 0.8302, 0.5493 and 0.1761 above 5 %. So there is no significant difference between the proposed laboratory method and the reference method (pressure chamber) for measuring the soil water retention curve.

Table 4 Statistical analysis of measured retention curve and pressure chamber values.

Soil	RMSE	GMER
1	0.1126	1.15
2	0.0882	1.03
3	0.1189	1.26

Discussion

The evaporation method is a widespread experimental method for estimating soil hydraulic properties. In this research, we have demonstrated the success of estimating soil retention parameters by RETC from an evaporation experiment on small soil cores and using a single sensor for measuring the pressure head in line with the work of Simunek *et al*. [10] and Wessoleck *et al*. [9], and we have extended the range of measurement to −1,990 cm. Estimated values of van Genuchten equation parameters, especially α and n, are of the same order as the parameters estimated by other authors using the evaporation method, for instance Bruckler *et al*. [20] and Fujimaki and Inoue [6] for sandy loam soils and Basile *et al*. [21] for sandy clay soils. However, the hydraulic conductivity curve has not been determined assuming that it can be estimated from the equation of van Genuchten [16]. Simultaneous estimation of the retention curve and unsaturated hydraulic conductivity using the Wind algorithm [5] could be an interesting perspective of this study. According to Abbasi *et al*. [1] salinity indirectly affects soil hydraulic properties by acting on the porosity and permeability, the study of the effect of salts on these properties is recommended.

Finally, the Levenberg-Marquardt optimization algorithm implemented in RETC presents some difficulties to optimize certain parameters of water content and hydraulic conductivity from collected data in field conditions (Wesseling *et al.*) [4], use of other optimization methods is also suggested. All these recommendations will be taken into consideration in future work.

Conclusions

A simple evaporation method was advanced in this study for estimating soil water retention proprieties of an unsaturated zone. The obtained estimation results are acceptable and have shown that the van Genuchten retention curve parameters are different from one layer to another. However, these results allowed us to get an idea of the range of these parameters for each soil layer, especially for the shape parameters *α* and *n*. These results are essential for modeling of water flow and salts transfer in the Bouhajla vadose zone.

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