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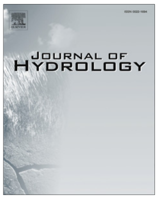

Investigating the relationship between unsaturated hydraulic conductivity curve and confined compression curve

Hossein Bayat [a,*], Azadeh Sedaghat [a], Ali Akbar Safari Sinegani [a], Andrew S. Gregory [b]

[a] Department of Soil Science, Faculty of Agriculture, Bu Ali Sina University, Hamedan, Iran
[b] Department of Sustainable Soils and Grassland Systems, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK

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SUMMARY

This study was conducted to estimate the soil unsaturated hydraulic conductivity through the van Genuchten model using easy to measure soil properties by regression and artificial neural networks methods. In this study, 148 soil samples were taken from five provinces of Iran. Basic soil properties (clay, silt/sand and bulk density) and other soil properties were measured. Soil water retention curve was measured to obtain the unsaturated hydraulic conductivity curve using the van Genuchten–Mualem model. Confined compression curve was measured and the modified model of van Genuchten was fitted on its data. Two-thirds and one-third of the data were used for the training and testing steps, respectively. Confined compression curve parameters and other soil properties were used as predictors to estimate unsaturated hydraulic conductivity curve. Pedotransfer functions (PTFs) were developed in two separate parts: in 5 and 6 PTFs basic soil properties were or were not used as predictors, respectively. The artificial neural networks (ANNs) performed better than the regression methods. Among the ANN-developed PTFs which have not used basic soil properties as predictors, PTF_{a3}, with the inputs of the parameters of confined compression curve (n^*, α^* and e_0), performed better than the others. Also, among the ANN-developed PTFs that used basic soil properties as predictors along with the other input variables, PTF_{b5} that used the σ_{mc} (stress at the maximum curvature) and σ_i (stress at the inflection point) as inputs along with basic soil properties, performed better than the other PTFs. The results showed a successful prediction of the hydraulic conductivity curve using confined compression curve.

1. Introduction

The moisture retention curve and unsaturated hydraulic conductivity (K) are hydraulic properties which control retention and movement of water in soil and are important input parameters in water and solute transport modeling. These properties are necessary in irrigation and drainage management. Field determination of K and moisture retention curves are often laborious and costly (van Genuchten and Leij, 1992), while measured values of K cannot capture the spatial variability under field conditions (Wilding, 1984). Therefore, pedotransfer functions (PTFs) have been developed and used as indirect methods (Van Genuchten, 1980; Wösten et al., 2001) to obtain hydraulic properties. The PTFs use easily measured soil properties, such as bulk density, particle size distribution and organic matter content, to predict soil hydraulic properties.

The compression characteristic describes the ability of a soil sample to resist deformation when subjected to an external force and shows the relationship between stress applied on a soil sample and a volumetric parameter such as strain, void ratio or porosity. Compression curves have two principal mechanical parameters: (i) the pre-compression stress (P_c) that shows the load support capacity of the soils and (ii) the compression index (C_c) that is the slope of the virgin compression line (Chaplain et al., 2011). Bulk density, water content, texture and organic carbon are the main factors affecting compression curves (Cui et al., 2010). The applied compaction causes a statistically significant increase in the soil's bulk density, and decreases its unsaturated hydraulic conductivity, which can lead to soil degradation (Zhang et al., 2006).

Kutílek et al. (2006) by analysing the pore size distribution of various soils reported a significant decrease of the pore size in the structural domain (meso-pores) by compression. Compression causes changes in meso and macro-porosity and a decrease of saturated hydraulic conductivity (Dexter et al., 2004; Gebhardt et al.,

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* Corresponding author. Tel.: +98 81 34424189 (office), +98 918 8188378 (mobile); fax: +98 81 34424189.

E-mail addresses: h.bayat@basu.ac.ir, hbayat2001@gmail.com (H. Bayat), azadehsedaghat65@gmail.com (A. Sedaghat), safari_sinegani@yahoo.com (A.A. Safari Sinegani), andy.gregory@rothamsted.ac.uk (A.S. Gregory).

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2006) as well as a decrease of air permeability (Horn et al., 1995). In addition, Wiermann et al. (2000) and Schäffer et al. (2007), by analysing the 3-D images of soil structure by X-ray tomography, reported that compaction of soil decreased both the porosity and the connectivity of the macro-pores. Cui and Delage (1996) observed that C_c increased with decreasing matric suction (increase of initial moisture content).

Tang et al. (2007) demonstrated three zones on the confined compression curve (Fig. 1):

(i) In zone I, where the vertical stresses are lower than the pre-compression stress, the volume change corresponds to the elastic deformation of the soil structure and the slope of the curve ($-de/d\log\sigma_v$) remains small; (ii) in zone II where the vertical stresses exceed the precompression stress, the volume change corresponds mainly to the reduction of the volume of the air-filled pores; (iii) in zone III, at high stresses, the volume of the air-filled pores becomes small and the reduction of meso-pores storing water dominates (Tang et al., 2007).

Similarly to the confined compression curve, unsaturated hydraulic conductivity curve (unsaturated hydraulic conductivity versus suction) have three regions (Fig. 2). In the first area, (part A in Fig. 2) the suction is low, all pores are saturated and hydraulic conductivity is high. In the second area (part B in Fig. 2) by increasing matric suction around the air entry value, the pores desaturate and hydraulic conductivity decreases rapidly. In the third region (part C in Fig. 2), more desaturation occurs and unsaturated hydraulic conductivity decreases by increasing matric suction (Alizadeh, 2007).

The decrease of hydraulic conductivity during compaction is also an important factor affecting the compaction curve (Tang et al., 2007). Tang et al. (2007) investigated the compression curve and observed that hydraulic conductivity decreased with increasing stress. They concluded that the reason may be the loss of air-filled pores and decreasing meso-pores by increasing suction. The same factors, such as moisture content, clay content and organic matter affect both unsaturated hydraulic conductivity and confined compression curves. Unlike the difficult and time consuming measurement of the unsaturated hydraulic conductivity curve, (Moustafa, 2000), measuring the confined compression curve is relatively quick and easy.

Baumgartl and Koeck (2004) used structure, bulk density, relative density and consolidation curve to model volume – stresses changes using the van Genuchten model. It means that the same model could describe both unsaturated hydraulic conductivity and confined compression curves. But, the relation of confined compression curve with unsaturated hydraulic conductivity curve has not been investigated in different soils, so far. Therefore, the objective of this study was to use the parameters of the confined compression curve models to estimate unsaturated hydraulic conductivity curve.

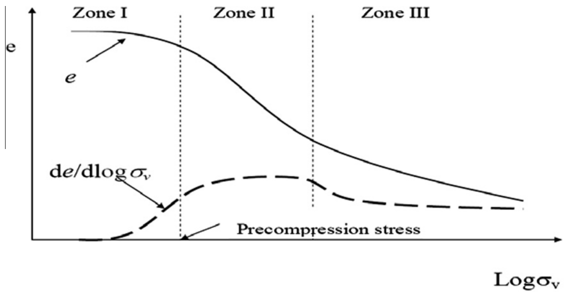

Fig. 1. The confined compression curve, divided into three zones by Tang et al. (2007).

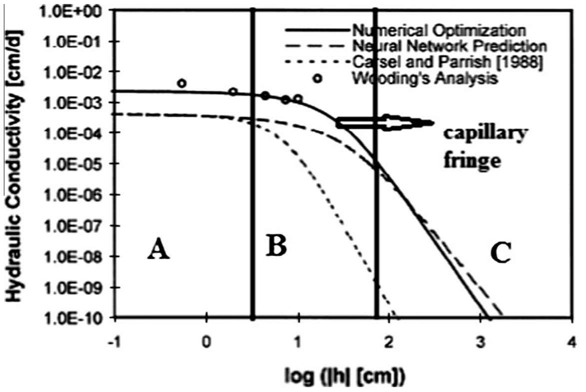

Fig. 2. The hydraulic conductivity characteristic curve. This figure is drawn based on the reports of the Carsel and Parrish (1988) and Alizadeh (2007).

2. Materials and methods

2.1. Soils

In this study, 148 disturbed and undisturbed soil samples were taken from surface (134 samples) and subsurface (14 samples) layers of five provinces of Iran, including Mazandaran (29 samples), Kermanshah (30 samples), West Azarbaijan (30 samples), East Azarbaijan (30 samples) and Hamedan (29 samples). The sampling depth varied from 3 to 15 cm for top-soils and from 15 to 43 cm for sub-soils depending on their thickness. Table 1 shows the geographical coordinates of the sampled provinces. Fig 3 shows the distribution of sampling points.

Some soil physical (particle size distribution and bulk density) and mechanical (precompaction stress, compression index, swelling index, void ratio, coefficients of the Gompertz model, van Genuchten model parameter modified by Baumgartl and Koeck (2004), stress at the inflection point and stress at the maximum curvature) properties were measured on the soil samples. To obtain the particle size distribution curve, soil samples were air-dried and sieved by a 2 mm sieve. The hydrometer technique was used to characterize soil particle size distribution (PSD) for the particles < 0.053 mm. Percentage of particles in fractions 0.053–0.1, 0.1–0.25, 0.25–0.5, 0.5–1.0 and 1.0–2.0 mm were characterized by the sieving method (Gee and Or, 2002).

2.2. Unsaturated hydraulic conductivity of van Genuchten model (1980)

The moisture content data were measured at suctions of 0, 1, 2, 4, 6, 10, 30, 100, 200, 400, 800 and 1500 kPa using sand box (0–6 kPa) and pressure plate apparatus (10–1500 kPa). The van Genuchten (1980) model was used to model soil water retention curve (SWRC) data. van Genuchten model (1980) is one of the most widely-used continuous SWRC models, which is applied for modeling the entire range of the soil matric suction. This model is expressed as following:

$$S_e = \frac{1}{[1 + (\alpha h)^n]^m} \tag{1}$$

where h is matric suction (kPa); m, n and α are shape factors of SWRC. The parameter α is described as the inverse of the air entry value. S_e is the effective saturation (–). The Solver optimizer software (Excel, 2010) was used to fit the van Genuchten (1980) model on the SWRC data using the Mualem (1976) assumption, ($m = 1 - \frac{1}{n}$). Then the parameters of van Genuchten model were used in the unsaturated hydraulic conductivity model of van