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Investigating the correlation between soil tensile strength curve and soil water retention curve via modeling

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ABSTRACT

Soil water retention curve (SWRC) is a crucial soil property required for solving many soil and water management problems. But, its direct measurement needs a lot of time, effort and money. The aim of this study was to develop pedotransfer functions (PTFs) for estimating water content through the van Genuchten (1980) model by employing tensile strength (TS) models. One hundred forty eight samples were gathered from five provinces in Iran. Bulk density, TS curve, SWRC and particle size distribution were measured. Four empirical TS models were fitted to the experimental soil mechanical data. Also, three physically based equations were used to estimate soil water content. In order to develop PTFs to estimate the parameters of van Genuchten (1980) model, artificial neural networks (ANNs) and regression (MLR) methods were used. In nine PTFs, the parameters of the empirical TS models and other soil properties were used as predictors for estimating SWRC. In developing the PTFs, ANNs were superior to MLR. Using the parameters of the TS models as predictors improved the estimation of water content between 2.8 and 6.9%. The SWRC was estimated better by using the parameters of the developed model of TS along with texture fractions and bulk density as predictors. The result showed the high capability of three physically based equations in the estimation of water content. Lu et al. equation had the highest accuracy in the SWRC estimation, in comparison with other physically based equations. The results showed the significance of TS in the estimation of SWRC.

1. Introduction

The soil water retention curve (SWRC), which defines the relationship between soil water content and hydraulic potential, is an important property of soil which controls its functioning in ecosystems and has a big effect on soil management (Rawls et al., 2003). There are many techniques to determine SWRC (Han et al., 2010). These methods fall into two categories: direct experimental methods and indirect estimation methods. The direct method is costly and time- consuming (Minasny et al., 1999). However, determination of the SWRC is not always costly and time-consuming. For instance, the multi-step outflow method can provide relevant information in a week at a relatively low cost (Van Dam et al., 1994). Pedotransfer functions (Huang et al., 2006) and physico-empirical methods (Hwang and Powers, 2003), are the current indirect methods (Janik et al., 2007). These methods are based on the relationship between volumetric soil water content and other soil features, such as soil texture, bulk density and organic matter content (Han et al., 2010). Identifying the most relevant soil structure parameters that can improve the estimation of SWRC parameters is an important area of developing PTFs.

Tensile strength is very sensitive to structural stability and has an important role in the mechanical properties of soil aggregates (Dexter and Kroesbergen, 1985; Watts and Dexter, 1998). Imhoff et al. (2006) and Seguel and Horn (2006) reported that TS increases with decreasing aggregates volume and diameter, respectively.

Soil strength is one of the dynamic properties of soils. It undergoes temporal and spatial changes as soil water content changes because of precipitation, irrigation, evaporation or plant uptake (Grant et al., 2001; Horn and Dexter, 1989; Watts and

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Dexter, 1998). When soil dries, its cementing agents such as soluble silica, $CaCO_3$ or dispersed clay will concentrate and then flocculate or precipitate at intra-aggregate contact points, leading to an increase in TS (Dexter, 1988; Kay and Dexter, 1992; Kemper and Rosenau, 1986; Lehrsch et al., 1991, 1993). TS can show the condition of soil (Dexter and Kroesbergen, 1985). Munkholm et al. (2007) showed the relation between TS of aggregates and the gravimetric water content. The aggregate-TS decreased with increasing water content (Munkholm and Kay, 2002) or decreasing matric suction. The relation between aggregate-TS and water content or matric suction has been called the TS curve (Watts and Dexter, 1998). Soil TS has a direct relation with bulk density (Guerif, 1990), soil organic carbon (Guimarães et al., 2009) and soil clay content (Ben-Hur and Lado, 2008; Kemper and Rosenau, 1986). TS is considerably sensitive to the microstructure of soil, and this makes it a valuable parameter in determining the structure and mechanical behavior of soil (Dexter and Watts, 2000).

The impact of matric suction on soil strength can be obtained using the shape of the drying branch of the SWRC (Aluko and Koolen, 2000). Soil TS increases by decreasing water content, especially by high fine particles in the soil (Hallett et al., 1995). Caron and Kay (1992) and Mullins et al. (1992) demonstrated a linear relationship between TS and matric suction in the range between 0 and 100 kPa. Empirical correlations between aggregate-TS and volumetric water content have been found in several studies (Causarano, 1993; Munkholm and Kay, 2002).

Furthermore, most of the above-mentioned soil properties that affect TS also have an effect on SWRC. High water content at constant matric suction is indicative of the high effective stress. So upon drying a soil, strength increases by increasing the effective stress (Mosaddeghi et al., 2006). Snyder and Miller (1989) highlighted the significance of pore characteristics in relation to TS. Aluko and Koolen (2000) reported a non-linear relationship between effective stress and soil strength. Snyder and Miller (1985) refined the effective stress method in a way to describe TS of unsaturated soils in the range of 0 and 1500 kPa matric suctions. The results of these experiments showed the relationships among TS, effective stress, and gravimetric water content. Drying of soil causes shrinkage due to the effective stress generated by the pore water pressure and the surface tension in the water menisci (Towner and Childs, 1972). As a result of this effect, drying a soil (e.g., in the process of measuring the SWRC) can alter the pore size distribution and accordingly the shape of the water retention curve relative to what it was in situ (Baumgartl et al., 2000; Katou et al., 1987).

Also, one of the main attributes of soil quality has been conventionally assumed to be soil structure (Kutilek, 2004). In order to optimize porosity, aeration, cumulative infiltration, the equilibrium infiltration rate, soil water retention curve (SWRC), and plant-available-water, it is essential to manage soil structure and aggregate properties (Jastrow and Miller, 1991). Being sensitive to soil structure, the soil physical condition can be evaluated by measuring tensile strength. In addition, it is controlled by micro-cracks or other flaws in the soil. Therefore, it is an indicator of the structural organization of soil (Watts and Dexter, 1998) and can be considered as a good estimator for SWRC. Because in the estimation of SWRC, it is very important to find the parameters such as TS that can quantify soil structure and use them as predictors. The other advantage of using TS as a predictor to estimate SWRC is that the TS can be measured easily and quickly by a cheap and simple apparatus. Whereas SWRC measurement is very expensive and time-consuming. Therefore, TS curve and SWRC are related to each other and each can be used to estimate the other. Emphasis is placed on the similarity of the shapes of the TS curve and SWRC and soil pore size distribution as well as variations in effective stress which affect both SWRC and TS curve.

Therefore, the objective of this study was the development of pedotransfer functions (PTFs) for van Genuchten parameters using the conventional physical data of soil as well as tensile strength information: both discrete measurements of tensile strength at specific matric suction and fitted parameters from tensile strength-matric pressure and tensile strength- water content were used as predictor variables.

1.1. Theory

1.1.1. van Genuchten (1980) SWRC model

The van Genuchten (1980) SWRC model was used in this study. Because, it is one of the most widely used SWRC models since it can exactly describe SWRC for most of soils (Leech et al., 2006):

$$S_e = \frac{1}{[1+(\alpha h)^n]^{(1-\frac{1}{n})}}, S_e = (\theta-\theta_r)/(\theta_s-\theta_r) \quad (1)$$

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h)^n]^{(1-\frac{1}{n})}} \quad (2)$$

Where, h is matric suction (cm). The parameter α (cm^{-1}) is inverse of air entry value, S_e is the effective degree of saturation, θ_r ($cm^3\,cm^{-3}$) and θ_s ($cm^3\,cm^{-3}$) are the residual and saturated water contents, respectively, and θ ($cm^3\,cm^{-3}$) is soil water content and depends on pore size distribution. In this study, van Genuchten (1980) model with Mualem hypothesis was fitted to the experimental data of SWRC by using RETC program (van Genuchten et al., 1991). We used m = 1-1/n in fitting the van Genuchten (1980) model to the experimental data of SWRC. Because it allows prediction of unsaturated hydraulic conductivity from water retention parameters (Schaap and Leij, 2000).

1.1.2. TS models

Tensile strength curve can be described by a model. Several models were used for the description of tensile strength curve (Ibarra et al., 2005; Watts and Dexter, 1998). These models quantify soil structure and demonstrate it in numbers. Structure development, which happens with a change in pore system, increases soil strength. When aggregation increases, strength increases and water retention curves start to be different from those reliant only on soil texture (Horn and Baumgartl, 2002). This underlines the importance of the TS models used in this study for estimating SWRC.

The Watts and Dexter (1998) (Eq. (3)), Ibarra et al. (2005) (Eq. (4)) models describe the relation between soil tensile strength and soil moisture. Ibarra et al. (2005) developed and demonstrated a technique for measuring tensile strength directly on soil samples prepared in laboratories. Their results were similar to those reported by Vomocil et al. (1961) and Farrell et al. (1967), who measured soil TS indirectly. Watts and Dexter (1998) proposed a second-order polynomial equation which showed the variation of aggregate strength at different water contents. The parameters of this model are empirical parameters.

1.1.2.1. TS empirical models

1.1.2.1.1. Watts and Dexter (1998) model. Watts and Dexter (1998) introduced the following model for the TS versus water content:

$$TS = g + i\theta_m + j\theta_m^2 \quad (3)$$

where, TS is the tensile strength (kPa), θ_m is the gravimetric water content in percent ($gr\,gr^{-1}$), and g, i and j are fitting parameters of the model.