Geoderma 318 (2018) 64–77

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Estimation of soil moisture using confined compression curve parameters

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Confined compression curve
Estimation
Pedotransfer function
Soil water retention curve

ABSTRACT

The confined compression curve (CCC) represents the relationship between the logarithm of the applied stress and the void ratio. There are several similarities between the soil water retention curve (SWRC) and the CCC. The aim of this study was to modify the Dexter SWRC model to fit the experimental CCC data by replacing the matric suction and water content in the Dexter model with the normal stress and void ratio, respectively, as well as using the CCC parameters and characteristics (pre-compression stress, compression, and swelling indices) as predictors to estimate the SWRC. We collected 150 soil samples from five provinces of Iran. The SWRC, CCC, and basic properties of the soil samples (clay, silt/sand, and bulk density) were measured. The Dexter model was applied to the experimental data for both the CCC and SWRC, and their parameters were calculated. The CCC parameters and basic soil properties were used to estimate the soil moisture at five input levels with the Dexter model. The best results were obtained using the basic properties of soil as predictors, as well as with the parameters of the Dexter model obtained by its fitting to the CCC data. The integral root mean squared error was reduced from 0.059 and 0.061 (in the first step) to 0.053 and 0.056 $g\,g^{-1}$ in the training and testing steps, respectively. The relative improvements in the SWRC estimates showed that improvements of 4.9% to 11.9% were obtained by using the CCC parameters as predictors. These improved estimates can be attributed to the apparent similarities between the two curves as well as the impacts of similar factors on these curves and the correlation between them.

1. Introduction

Soil compaction is caused by a number of different factors that can destroy the soil structure, reduce soil porosity, decrease the infiltration capacity of water, and also change the arrangement of soil particles. Compaction affects the soil water retention curve (SWRC) and mechanical properties by changing the soil structure. In soil engineering, the soil deformation is evaluated as elastic (instantaneous) or plastic (long term) depending on the intensity of the stress (Baumgartl and Koeck, 2004). Keller et al. (2011) showed that the graph of the log stress (logσ) versus the void ratio (e) for an unsaturated soil can be used to describe the compression of the soil. This curve is called the confined compression curve (CCC) and it has three important parameters: the pre-compression stress (P_c), the swelling index (C_s), and the compression index (C_c) (Fig. 1).

P_c is often obtained by plotting the void ratio or vertical strain of soil versus the logarithm of the vertical pressure stress (Casagrande, 1936). The CCC has two separate areas that represent the elastic behavior at low stresses (recompression or swelling line) and the permanent deformation (virgin compression line) at higher stresses (Fig. 1). P_c is the stress indicating changes in the elastic behavior to plastic behavior (Cavalieri et al., 2008). Thus, P_c is the maximum stress that soils have ever experienced. Permanent soil compression will occur when the applied stress exceeds P_c. However, whenever the applied stress is lower than the P_c, the soil will be recompressed after compression.

The absolute value of the slope of the virgin compression line is called the compression index (C_c), which is considered to be an indicator of a soil's resistance to compaction, as well as being used as a criterion for measuring the soil compressibility (Fig. 1). The resistance of the soil to compression will be lower when C_c is higher, and the compression will occur very rapidly after small changes in the applied stress. The slope of the virgin compression line is very important for analyzing and calculating soil settlement (Larson et al., 1980).

The absolute value of the elastic area slope of the CCC is the swelling index (C_s), which is used as a measure of soil mechanical resilience. C_s is significantly smaller than C_c and it can normally be obtained from experimental results (Fig. 1). The soil resistance to compression will be higher when C_s is larger. Thus, larger values of C_s indicate that the soil will be recompressed after compression by removing the applied stress.

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https://doi.org/10.1016/j.geoderma.2017.12.034
Received 3 November 2016; Received in revised form 7 December 2017; Accepted 29 December 2017

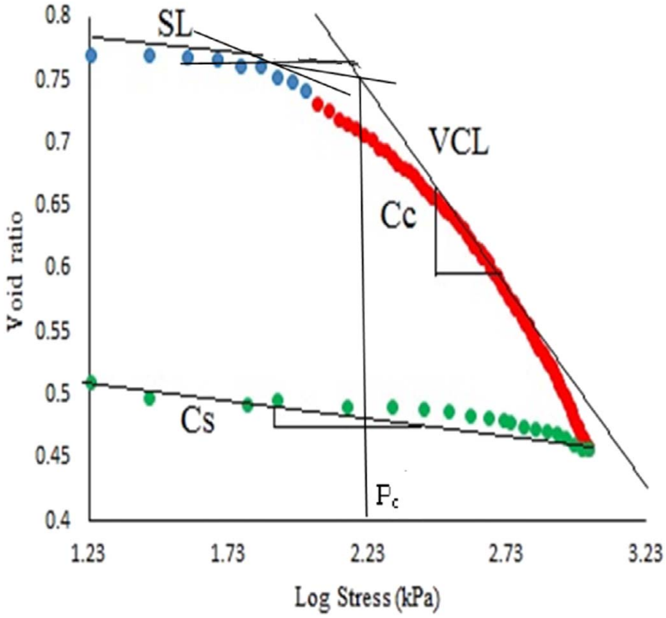

Fig. 1. Confined compression curve and its components. C_c is the compression index, C_s is the swelling index, P_c is the pre-compression stress, VCL is the virgin compression line, and SL is the swelling line.

The stress/void ratio graph or CCC is very similar to the SWRC. These two curves start from an upper point and then decrease, before increasing on the horizontal axis. Furthermore, the shapes of the curves are changed by variations in the pore size distribution (Baumgartl and Koeck, 2004; Schoonover and Jackie, 2015). Dexter et al. (2008) reported that the soil structure is associated with the SWRC. Soane and Van Ouwerkerk (1994) and Chan et al. (2006) also stated that the CCC is a function of the soil structure, whereas the SWRC is a function of the three phases comprising solid, liquid, and air in the soil (Sillers et al., 2001). In addition, some studies have demonstrated that increasing the clay content of the soil causes increases in P_c and C_c (Gregory et al., 2006; Saffih-Hdadi et al., 2009). In the SWRC, increasing the clay contents enhances the retention of soil water, as well as increasing the air entry suction and reducing the slope of the curve in the middle area. Baumgartl and Koeck (2004) reported that the suction and stress are two common parameters for both curves where they lie on the horizontal axis in the graphs. Zhang et al. (2017) stated that there is a relationship between the SWRC and soil compaction. Moreover, low compaction of soil leads to an increase in water retention at higher matric suctions because soil compression reduces the macroporosity, which is responsible for drainage and water withdrawal from the soil.

In recent years, pedotransfer functions (PTFs) have become increasingly popular for estimating the hydraulic properties of soil (Lamorski et al., 2008; Twarakavi et al., 2009). PTFs are regression equations or other models (e.g., artificial neural networks) that correlate difficult to measure soil properties, such as the soil hydraulic properties, with more readily available soil data, including the texture, organic matter content, and bulk density (BD) (Gupta and Larson, 1979). Thus, PTFs transform “what we have” into “what we need” (Wösten et al., 2001). As an indirect approach, PTFs are among the most widely used tools employed for predicting the SWRC. Obtaining direct measurements of the SWRC is time consuming, expensive, and highly laborious, so many attempts have been made to predict the SWRC indirectly by using different methods based on both the physical and chemical properties of soil (Nguyen et al., 2014, 2017).

In previous studies, various parameters have been used in PTFs to estimate the SWRC, including the soil texture (Lee and Ro, 2014), organic matter, BD (Meskini-Vishkaee et al., 2014), soil saturated hydraulic conductivity (Vereecken et al., 1992), soil genetic data (Tietje and Tapkenhinrichs, 1993), cation exchange capacity (Pachepsky and Rawls, 1999), penetration resistance (Pachepsky et al., 1998), specific surface area (Walczak et al., 2004), geometric specific surface (Walczak et al., 2006), fractal parameters of particles and aggregates (Bayat et al., 2011; Bayat et al., 2013), and micro-aggregate size distributions (Ebrahimi et al., 2014b). Despite the use of different soil properties for developing PTFs, it is still challenging to obtain accurate predictions of the parameters for SWRC models in soil physics, and thus the water contents. In addition, the selection of the input variables employed will always depend on the specific data set and the region considered. In arid countries where the soil organic matter contents are usually low, this parameter will rarely be significant when estimating the SWRC compared with data sets obtained from temperate or cold regions of the world. Therefore, finding new input variables that are readily available and correlated with the output variables in the study region would facilitate the development of PTFs.

There are some close relationships between the SWRC and CCC, but measuring the SWRC is far more expensive and time consuming than measuring the CCC. In fact, the CCC cannot be measured as easily as readily available soil properties such as the soil texture, but it can be measured quickly. Expensive equipment such as a pressure plate and sandbox are required to measure the SWRC, which are not available everywhere, whereas the CCC can be measured using a relatively simple single-axis apparatus, which is much cheaper than both a pressure plate and sandbox. Thus, the CCC can be determined in less time and at a lower cost.

Functions that only use very simple data as input variables, e.g., soil texture, have lower precision when estimating the soil moisture. The moisture content is a function of many factors, and thus the moisture retention cannot be described fully by using features such as the soil texture. Soil mechanical properties such as the CCC have strong impacts on soil moisture retention (Gregory et al., 2006; Imhoff et al., 2004; Keller and Arvidsson, 2007; Lebert and Horn, 1991) because they are correlated with the soil particle size distribution (Gregory et al., 2006; Imhoff et al., 2004; Lebert and Horn, 1991), organic matter (Kuan et al., 2007), soil structure (Ekwue, 1990), BD, and pore size distribution (Culley and Larson, 1987; Horn, 2004). In previous studies, the CCC and its coefficients have not been used to estimate the SWRC although they contain large amounts of information regarding the soil mechanical properties, so using them as predictors might improve estimates of the SWRC.

The Dexter model is a bimodal model and its parameters have physical meaning (Dexter et al., 2008), whereas the van Genuchten model is a unimodal model. Bimodal models are more accurate compared with unimodal models for aggregated soils, including the soils used in this study where the pore size distribution of the soils contained two peaks (the peaks indicate the pore size(s) with the maximum density if the pore size distribution is represented in the form of density values) (Seki, 2007). Thus, one of the advantages of the present study is the use of the bimodal Dexter model instead of the unimodal van Genuchten–Mualem model. The objectives of the present study were: (1) to modify the Dexter et al. (2008) SWRC model to fit to the experimental CCC data; and (2) to use the CCC parameters and characteristics (such as P_c, C_c, and C_s) as predictors to estimate the parameters of the Dexter et al. (2008) SWRC model, and thus the soil moisture content.

1.1. Theory

Dexter et al. (2008) presented a model based on the fact that the porosity of soil comprises four components, i.e., the residual porosity representing very fine pores in soil, the porosity of the soil matrix, the structural porosity comprising the pore spaces among the micro-aggregates and among incipient aggregates, and the macroporosity due to