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Estimation of unimodal water characteristic curve for gap-graded soil

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Abstract

Soils with a bimodal grain-size distribution (gap-graded soils) can be associated with unimodal or bimodal soil-water characteristic curves (SWCCs). Many equations have been developed to estimate SWCCs using grain-size distribution curves to overcome the high cost and long duration of SWCC experiments. Most of the equations are limited to the estimation of the SWCCs of soils with a unimodal grain-size distribution. Few studies have been conducted on the estimation of unimodal SWCCs for gap-graded soils. In this paper, procedures, equations and computer codes are proposed for estimating the unimodal SWCCs of gap-graded soils. The proposed equations are found to perform well in estimating the unimodal SWCCs of gap-graded soils.

Keywords: Grain-size distribution; Unimodal soil-water characteristic curve; Soil mixture; Gap-graded soil

1. Introduction

Soil-water characteristic curves (SWCCs) describe the variations in water content with respect to soil suction (Fredlund and Rahardjo, 1993). Fredlund (2006) suggested plotting SWCCs in terms of the volumetric water content (θ_w) against the matric suction (u_a-u_w). The typical shape of SWCCs is sigmoidal; the curves are commonly plotted on a logarithmic scale over the entire range in suction. The main variables of SWCCs are saturated volumetric water content θ_s, residual volumetric water content θ_r, air-entry value ψ_a and water-entry value ψ_w. The air-entry value is defined as the matric suction at which air first enters the largest pore of the soil. The residual volumetric water content is defined as the volumetric water content at which further increases in matric suction do not result in any significant decreases in the volumetric water content. Matric suction at the inflection point is defined as the matric suction at which the volumetric water content of the soil specimen decreases rapidly. Soils with different textures and grain-size distributions have different SWCCs (Gallage and Uchimura, 2010; Rahardjo et al., 2012c). Sandy soils usually have a low air-entry value and an SWCC with a steep slope (Fig. 1). The air-entry value of silty soils is higher than that of sandy soils due to the presence of smaller pores.

Grain-size distribution with bimodal characteristics is commonly observed in residual and colluvial soils (Rahardjo et al., 2012a; Zhang and Chen, 2005). These types of soils are known as gap-graded soils. Some gap-graded soils result in dual porosity soils where the soil-water characteristic curve (SWCC) shows bimodal behaviour (Rahardjo et al., 2014, 2012b; Stoicescu et al., 1998), while other gap-graded soils have an SWCC with

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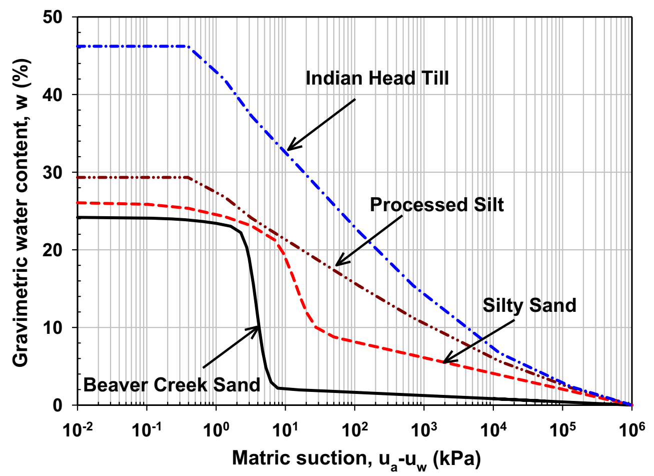

Fig. 1. SWCCs from different types of soil (modified from Fredlund et al., 2012).

unimodal characteristics (Priono et al., 2016). Continuous mathematical functions are required to represent the grain-size distribution of soils and SWCCs. A mathematical equation for a grain-size distribution curve can be used to classify the soil and to estimate the SWCC (Fredlund et al., 2012). On the other hand, a mathematical equation for SWCCs can be used to determine the SWCC variables, such as the air-entry value, the inflection point, the residual water content and the residual suction (Wijaya and Leong, 2016; Zhai and Rahardjo, 2012; Sheng and Zhou, 2011; Sheng, 2011; Fredlund and Xing, 1994; Kosugi, 1994). The mathematical equation for SWCCs can also be used to minimize the time required for the experimental works performed to determine SWCCs in the laboratory.

Many equations have been proposed to estimate the SWCCs from the grain-size distribution since the measurement of SWCCs is relatively time-consuming and expensive. Huang et al. (2010) classified the equations used to estimate SWCCs into two groups: equations to estimate SWCCs based on the statistical relationship among the soil properties (Meskini-Wishkaee et al., 2014; Fredlund et al., 2012; Schaap and Leij, 1998; Vereecken et al., 1989) and equations to estimate SWCCs based on the physico-empirical approach (Chin et al., 2010; Hwang and Powers, 2003; Haverkamp et al., 1999; Arya and Paris, 1981). Arya and Paris (1981) proposed the idea of dividing the soil element into several fractions in a discrete domain with each fraction having the same porosity for estimating the SWCCs for soil as the unimodal grain-size distribution. There are two major assumptions made in this model: (i) that the solid volume in any given assemblage can be approximated as that of uniform-size spheres defined by the main particle radius for the fraction and (ii) that the volume of the resulting pores can be approximated as that of uniform-size cylindrical capillary tubes whose radii are related to the main particle radius for the fraction. Based on this model, a grain-size distribution will be translated into a pore-size distribution. Then, the pore radii can be converted into matric suction using the capillarity equation. The cumulative pore volume with respect to the pore radii can be divided by the total volume to generate the volumetric water content with respect to the pore radii. The model developed by Arya and Paris (1981) performed well in estimating the SWCCs of soils with grain-size distributions that have unimodal characteristics.

All other existing equations can only be used to estimate unimodal SWCCs for soils with a unimodal grain-size distribution (i.e., Perera et al., 2005; Fredlund et al., 2012; Zapata, 1999) or to estimate bimodal SWCCs for soils with a bimodal grain-size distribution (i.e., Alonso et al., 1987; Bagherieh et al., 2009). None of the existing equations can be used to estimate the unimodal SWCCs for soils with a bimodal grain-size distribution (gap-graded soils). Therefore, several equations are proposed in this study to describe the relationship between variables in a bimodal grain-size distribution of gap-graded soil and variables in a unimodal SWCC. In addition, the computer codes for the computation of unimodal SWCCs for gap-graded soils are developed. The scope of this work includes the measurement of SWCCs using a Tempe cell and a pressure plate in the laboratory for different compacted soils. The results of the SWCC tests in this study and the SWCC data from published literature are used to validate the proposed equations for the estimation of a unimodal SWCC for a gap-graded soil.

2. Mathematical equations for best fitting grain-size distribution and soil-water characteristic curve

An appropriate mathematical equation with a clear physical definition is required to represent the grain-size distribution curve of soil and a soil-water characteristic curve (SWCC) since the equation will be used to relate the grain-size distribution curve and the SWCC. The term for the physical definition refers to the ability of the parameters in the equation to represent the variables of the grain-size distribution of the soil and the SWCC. In this study, Satyanaga et al.'s (2013) grain-size distribution equation was used to best fit the grain-size distribution of gap-graded soil since the parameters of the equation represent the variables of the grain-size distribution.

The equation for the best fitting grain-size distribution with bimodal characteristics is as follows:

$$P = \left[1 - \left(0.15\ln\left(1 + \frac{0.075}{d}\right)\right)\right] \times \left[W_1\left(erfc\frac{\ln\left(\frac{d_{\max\ 1} - d_{m1}}{d_{\max\ 1} - d}\right)}{s_{d1}}\right) + W_2\left((\beta_1) + (\beta_2)erfc\frac{\ln\left(\frac{d_{\max\ 2} - d_{m2}}{d_{\max\ 2} - d}\right)}{s_{d2}}\right)\right] \quad (1)$$

where

$\beta_1 = 1$ when $d \le d_{max2}$; $\beta_1 = 0$ when $d > d_{max2}$
$\beta_2 = 0$ when $d \le d_{max2}$; $\beta_2 = 1$ when $d > d_{max2}$