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Water characteristic curve of soil with bimodal grain-size distribution

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ABSTRACT

Soil–water characteristic curve (SWCC) is the most fundamental and important soil property in unsaturated soil mechanics. It has been used for analyzing slope stability due to the infiltration of rainfall into slopes and water flow in unsaturated embankments. Generally, SWCC is obtained by laboratory tests. However high cost, long duration and difficulty of the tests impede the application of unsaturated soil mechanics to practical design or analysis. Therefore, several equations have been developed to predict the SWCC using grain-size distribution (GSD) curve. However, most of the equations were limited to soils with unimodal characteristics and the parameters of the equations are not related to the physical properties of the soil. In this paper, an equation to predict SWCC for soils with bimodal characteristics is proposed. The parameters of the proposed equation are related to the physical properties of soil and the variables of SWCC closely. The proposed equation is evaluated with data from the literature and laboratory tests carried out in this study. In addition, the computer codes for the computation of the predicted bimodal SWCC are presented.

1. Introduction

Many residual and colluvial soils show bimodal grain-size distribution (GSD) [45,56]. Some soils with bimodal characteristic of GSD result in bimodal characteristic of SWCC, whereas others result in unimodal characteristic of SWCC. Bimodal SWCC is usually associated with a bimodal pore-size distribution according to the capillary theory [15,53]. Durner [19] indicated that bimodal pore-size distribution could be observed within soil particle with bimodal GSD. Zhang and Chen [56] observed that two pore series in the dual-porosity soil are governed by the coarse grains (large pores) and the fine grains (small pores). This phenomenon occurred since fine grains do not completely fill the pores formed by the coarse grains (Fig. 1).

Modeling GSD and SWCC with a continuous function is advantageous. The GSD model can be used to classify the soil and predict the SWCC. On the other hand, the SWCC model can be used to obtain soil properties, such as: the air-entry value, residual water content and water-entry value. The SWCC model can also be used to reduce the required time for the SWCC tests in the laboratory. Several researchers used parametric models of the full distribution of particle sizes [14,49,21,30] and others used statistical transformation of limited three-fraction texture data [50] for modelling GSD. Among all GSD equations, only Fredlund et al. [21] equation can be used to fit bimodal GSD. However, the parameters in their equation are not related to the physical properties of soil.

Various equations have been proposed to represent a unimodal SWCC [42,43,25,35,39,22,54] and a bimodal SWCC [37,56]. Zhang and Chen [56] compared the performance of their equation with other equations for fitting a bimodal SWCC. The result indicated that their equation performed the best among other SWCC equations. However, the parameters in their equation are not related to the physical properties of soil and the variables of SWCC.

Measurement of the SWCC in the laboratory and in the field is relatively time consuming and expensive. Therefore, several models have been proposed to predict SWCC from GSD. Such models are known as Pedo-Transfer Functions. Huang et al. [29] classified Pedo-Transfer Functions into two groups: estimation of SWCC based on statistical relationship between soil properties [55,48,20] and estimation of SWCC based on physico-empirical approach [2,28,27,3,57,30,16,4,17] and [40]. Rouault and Assouline [47] modelled the relationships between GSD and pore-size distribution of the multicomponent packed sphere case and they applied the model to soil. Haverkamp et al. [27] and Hwang et al. [31] improved the model and observed that there is non-linear relationship between soil particle and soil pore size based on this model.

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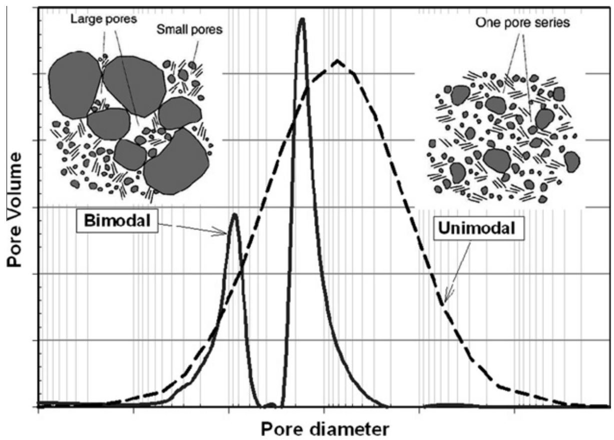

Fig. 1. Structure and pore-size distribution of soils with unimodal and bimodal characteristics.

A lot of research works have been carried out to study the SWCC of soils with bimodal characteristics. It is concluded that SWCC of a soil is not only related to the GSD of the soil, but also related to the structure of the soil [1,34,24,38,41]. Bimodal soils commonly have two levels of structure: the soil microstructure (the elementary particle associations within the soil aggregates) and the macrostructure (the arrangement of the soil aggregates). Several equations have been developed to predict SWCC from GSD. However, the existing equations are limited to soils with unimodal characteristics and none of the existing equations can be used to quantify the relationship between the SWCC and the soil structure for soils with bimodal GSD [20,30,29]. Previous research works also did not reveal whether soils with bimodal GSD will result in unimodal or bimodal SWCC. Therefore, a new equation to predict the SWCC of a soil with bimodal characteristics is proposed in this paper. The proposed equation incorporates parameters which are related to the physical properties of soil and the variables of SWCC closely.

2. Soil–water characteristic curve

SWCC defines the relationship between volumetric water content, θ_w, and matric suction, $(u_a–u_w)$. The shape of a unimodal SWCC is sigmoid and it has two paths, drying and wetting, due to hysteresis [23]. Fig. 2 shows the drying and wetting SWCCs and their key variables are: saturated volumetric water content for drying curve, θ_s, saturated volumetric water content for wetting curve, θ_a, 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 pores of soil. The residual volumetric water content is defined as the volumetric water content at which further increases in matric suction do not result in significant decreases in the volumetric water content. Matric suction at the inflection point is defined as the point at which the degree of saturation of the soil specimen decreases rapidly.

Soils with different textures and pore-size distributions have different SWCCs [11]. Sandy soils usually have a low air-entry value and a steep slope of the SWCC [13]. Silty soils and sandy soils usually have a similar shape of SWCC. However, the air-entry value of silty soils is higher than that of sandy soils due to the presence of smaller pores. Clayey soils have air-entry values higher than those of sandy and silty soils and residual water contents that cannot be visually identified [12].

3. Proposed equation for predicting SWCC

An appropriate mathematical equation with clear physical meaning is required to represent SWCC since SWCC is the important properties of unsaturated soil in seepage analyses. Leong and Rahardjo [39] and Sillers et al. [51] reviewed equations of SWCC. They observed that the parameters of the existing equations are not individually related to shape of the SWCC. As a result, unique values of the parameters are difficult to obtain and the parameters of the existing equations are not related to the variables of SWCC. Fredlund et al. [21] carried out statistical assessments of several SWCCs and they observed that the grouping of soils with typical parameters of the SWCC equation are difficult.

In this paper, a new equation to represent bimodal SWCC is proposed. The proposed SWCC equation is developed considering several factors, such as:

1. The parameters in the proposed equation can be related to the physical properties of the soil and have clear physical meaning. The term of physical meaning for parameters in the SWCC equation refers to the ability of the parameters in the proposed equation to represent the variables of the SWCC, such as: air-entry value of soil, inflection point of SWCC, and residual suction and residual water content of soil (Fig. 3).
2. The water content of soil is set equal to zero when suction of soil reaches 10^6 kPa [46]. Therefore, the correction function from Fredlund and Xing [22] is adopted in the proposed SWCC equation.

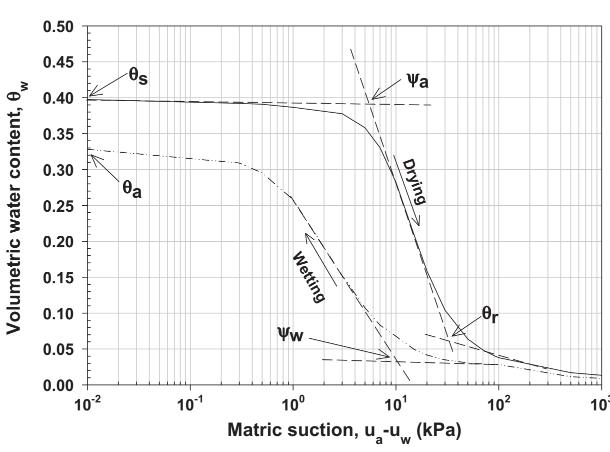

Fig. 2. Definition of terms for a typical soil–water characteristic curve.

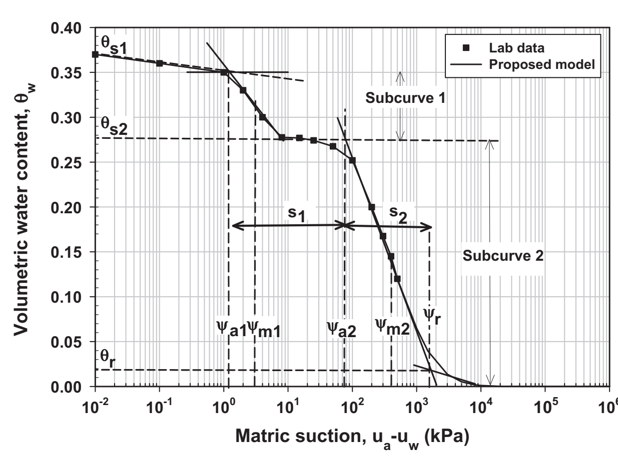

Fig. 3. Soil–water characteristic curve with bimodal characteristic.