Computers and Geotechnics 57 (2014) 85–96

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Predicting bimodal soil–water characteristic curves and permeability functions using physically based parameters

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ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 5 January 2014
Accepted 5 January 2014
Available online 7 February 2014

Keywords:
Soil water characteristic curve
Dual-porosity
Permeability function
Unsaturated soil
Grain-size distribution

ABSTRACT

Experimental evidence shows that a gap-graded soil or a widely-graded granular material may have a bimodal soil–water characteristic curve (SWCC) and a bimodal permeability function. A bimodal SWCC or a bimodal permeability function originates from a dual-porosity structure. To date, the prediction of bimodal SWCCs for gap-graded soils is still a difficult task. In this paper, a bimodal SWCC model is proposed to describe the drying process of granular soils considering a dual-porosity structure. The new SWCC model shows powerful capability in fitting the SWCCs for soils varying from gravel to silt. Regression analysis is conducted to establish empirical relations between the model parameters and the indexes of soil grain-size distribution (GSD). Based on these relations, the new model predicts well both the bimodal SWCCs for gap-graded soils and the unimodal SWCCs for well-graded soils and uniform soils. A bimodal permeability function is also proposed and linked to the new SWCC model. In the absence of experimental SWCCs and permeability functions, the new model can be used to obtain preliminary SWCCs and permeability functions for granular soils. It should be mentioned that the prediction of the SWCC from the GSD is still empirical and does not address the cyclic wetting/drying process. Measurement of the SWCC should be performed wherever an accurate SWCC is required.

1. Introduction

The water retention ability of a soil is usually characterized by a soil–water characteristic curve (SWCC) or a soil-retention curve. SWCC is widely used in geotechnical, geoenvironmental and agricultural engineering [36]. A SWCC is an important soil parameter function to conduct seepage analysis for saturated/unsaturated soil systems [44]. A SWCC is also a basis to determine other important soil properties such as unsaturated permeability [11] and shear strength [42].

The measurement of SWCC is often time consuming. It would be convenient to estimate the SWCC from basic soil properties, such as grain size distribution (GSD) and void ratio, in engineering practice. In soil science, pedo-transfer functions (PTF) are used to predict certain soil properties through data from soil surveys [6]. There are three general categories of grain-size distributions [19]: well-graded soils, uniform soils, and gap-graded soils. In the categories of well-graded soils and uniform soils, SWCCs often show unimodal features [10,47]. For unimodal soils, PTFs have been proposed based on soil particle-size distributions [1,13] and other geotechnical properties [12] such as void ratio and plasticity index. Many unimodal SWCC models have also been proposed to fit SWCC test data, as listed in Table 1, and show good fitting ability [33].

A bimodal SWCCs may be associated with any soil with a dual-porosity structure [3,45,29], such as gap-graded soils [35,45], soils compacted at the dry side of optimum [34], compacted coarse colluvial soils [26], coarse colluvial soils with high coarse fractions [29,46,48,49], and other structured soils [45]. Fredlund et al. [10] proposed a bimodal soil water characteristic curve (SWCC) model, which uses superposition of two unimodal SWCCs described by Fredlund and Xing [11]. Gitirana and Fredlund [16] proposed another bimodal SWCC model using parameters that have physical meanings. These models well fit experimental results [10,16]. However, the prediction of bimodal SWCCs is a difficult task so far if the measured bimodal SWCC is absent. To date, SWCC PTFS are based on the assumption of a unimodal SWCC and are not capable of predicting bimodal SWCCs. There is still a lack of a PTF that is capable of predicting bimodal SWCCs. This paper aims to develop a general SWCC PTF for granular soils, which is able to predict the bimodal SWCCs for gap-graded soils. Since a bimodal SWCC originates from a dual-porosity structure, the new general SWCC model is first developed based on the dual-porosity structure. To

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http://dx.doi.org/10.1016/j.compgeo.2014.01.004

Table 1
Summary of soil-water characteristic curve models.

Model name	Expression	Parameters
Burdine [2]	$S = 1/(1 + (a\psi)^n)^{1-2/n}$	a, n = constant
Gardner [15]	$S = 1/(1 + a\psi^n)$	a, n = constant
Brooks and Corey [4]	$\theta = (\psi_a/\psi)^{\lambda}$	λ = pore-size distribution index
Brutsaert [5]	$S = 1/(1 + (\psi/a)^n)$	a, n = constant
Campbell [7]	$\frac{\psi}{\psi_a} = \left(\frac{\theta}{\theta_s}\right)^{-b}$	b = constant
Mualem [31]	$S = (1 + (a\psi)^n)^{-1+1/n}$	a, n = constant
van Genuchten [41]	$S = (1 + (a\psi)^n)^{-m}$	a, n, m = constant
Williams et al. [43]	$\ln\psi = a + b\ln\theta$	a, b = constant
Mckee and Bumb [28]	$S = \exp(-\psi/b)$	b = constant
Fredlund and Xing [11]	$S = (\ln(e + (\psi/a)^n))^{-m}$	a, n, m = constant
Kosugi [20]	$S = 0.5 erfc\left(\left[\ln\left(\frac{\psi_a - \psi}{\psi_a - \psi_{mode}}\right) - \sigma^2\right] / \sqrt{2}\pi\sigma\right)$	σ = constant; $erfc$ = complimentary error function; ψ_{mode} = mode related to pore-size distribution
Gallipoli et al. [14]	$e(p'', \xi) = \frac{e}{e_s}(\xi) e_s(p'')$	$e(p'', \xi)$ = the normal compression state surface; $e_s(p'')$ = the saturated normal compression line; ξ = bonding variable; p'' = isotropic average skeleton stress; e_s = the void ratio at saturated state
Li [27]	$s^* = \alpha^* \pm (\lvert\bar{s}^* - \alpha^*\rvert^{\beta+1} - \lvert\bar{s}_0^* - \alpha^*\rvert^{\beta+1})^{1/(\beta+1)}$	S^* = $\ln\psi$; α^* = $\ln\alpha$; α = the impact of wetting/drying history; $\bar{s}^*$ = $\ln\bar{s}$; β = material parameter; $\bar{s}_0^*$ = the value of $\bar{s}^*$ at the beginning of the scanning curve
Tarantino [38]	$S = \left\{1 + \left[\left(\frac{e}{a}\right)^{1/b} s\right]^n\right\}^{-b/n}$	a, b, n = *soil parameter*; e-void ratio
Pedroso and Williams [33]	$S = -\lambda s + \frac{1}{\beta}\ln(c_3 + c_2 e^{c_1 s})$	$s = \ln(1 + \psi)$; λ = tangent inclination for the reference curve; β fitting coefficient; c_1, c_2, c_3 parameters depend only on the constitutive parameters and differs with wetting/drying history
Tsiampousi et al. [40]	$S_{r,pr}^{dr.wet} = \frac{1-(1/s_0^*)s^*}{1+\alpha_{d,w}s^*}$ $S_{r,scan}^{dr} = S_{r,A} - r_{dr} + [r_{dr}^2 + (logs^* - logs_A^*)^2]^{1/2}$	$S_{r,pr}^{dr.wet}$ = primary drying or wetting curve; $S_{r,scan}^{dr}$ = scanning drying curve; s^* = combined suction; s_A^* = combined suction at a retention point A; s_0^* = combined suction at degree of saturation of 0.0; α-fitting parameter; $S_{r,A}$ = degree of saturation at retention point A; r_{dr} = radius of the circle

S is the degree of saturation; θ is the volumetric water content; ψ is the matric suction; ψ_a is the air entry value; θ_r is the residual water content; θ_s is the saturated water content.

calibrate the model, a statistical analysis is conducted based on existing experimental data. Statistical relations between the model parameters and the soil GSD are then established and used to predict the SWCCs. The fitting and prediction capacity of the new model is further tested by measured SWCCs for granular soils. Soil with a dual-porosity also presents a bimodal permeability function and has connection with its SWCC. Finally, a bimodal permeability function PTF is also proposed and linked to the new SWCC model. It should be mentioned that, the prediction of SWCC from GSD is highly empirical and cannot substitute the measurement of the SWCC. The model should not be used to predict an SWCC where cyclic suction is anticipated. These predictions can be used in preliminary design and analysis.

2. Experimental data and regression analysis

Li [23] reports a series of SWCC and permeability functions measured in the laboratory, where bimodal SWCCs and permeability functions are found for a well-graded gravel with sand (GW-GM with silty fines with sand) and a silty sand with gravel (SM with gravel). The grain size parameters and the unsaturated soil properties of these soils are listed in Table 2. These data are used in this paper for model calibration. Details of the SWCC test procedure can be referred to Li et al. [24] and the permeability test procedure can be referred to Li et al. [25].

Other experimental data used include a dataset of 44 soils, which was selected from the research literature to test the proposed bimodal SWCC model. These data are from SS1996 dataset, US2000 dataset, SP1022 dataset, RS2000 dataset, and SP1020 dataset in the database of Soilvision [37]. All of the selected soils were granular materials (silty soil, sandy soil or gravelly soil) and their GSDs and SWCCs were measured. Some GSDs of these soils are listed in Table 2 as well and used to predict their SWCCs.

3. Bimodal SWCC equation

According to the capillary theory, a bimodal SWCC is associated with a bimodal pore- size distribution or a dual-porosity structure.

Table 2
Parameters estimated from soil GSD and void ratio for the bimodal SWCC model (Eqs. 13-17).

Soil type	Void ratio	d_{10} (mm)	d_{30} (mm)	d_{60} (mm)	w_s	ψ_a (kPa)	w_r	ψ_r (kPa)	ψ_t (kPa)	ψ_{a2} (kPa)	Fig. name	Reference
CL with sand	0.98	0.0019	0.0071	0.0302	0.370	21.0	0.058	4000	–	–	Fig. 5	Li [23]
GW-GM with sand	0.59	0.26	2.94	8.21	0.224	0.049	0.025	34.3	0.19	0.40	Fig. 13d	Li [23]
SM with gravel	0.63	0.0067	0.22	5.5	0.238	0.292	0.033	1016	4.65	20.7	Fig. 13c	Li [23]
Silt loam	1.29	0.0008	0.0199	0.0724	0.49	6.985	0.048	1412	72	116	Fig. 12a	RS2000
Loam	0.73	0.00003	0.0293	0.0809	0.27	1.682	0.039	35681	53	185	Fig. 12b	SP1020
Sandy Loam	0.61	0.0019	0.1397	0.4108	0.23	0.637	0.025	1550	6.85	44.5	Fig. 12c	SP1020
Loamy sand	0.64	0.0569	0.1216	0.1835	0.24	2.114	0.022	32.7	7.49	6.07	Fig. 12d	SP1020
Sand	0.66	0.1229	0.1738	0.2541	0.25	1.664	0.021	17.7	4.83	3.66	Fig. 13a	SP1020
Well graded gravel	0.51	1.2047	5.4907	11.8259	0.19	0.034	0.020	8.97	0.087	0.15	Fig. 13b	SP1022

RS2000 and SP1020 are the dataset IDs in SoilVision database [37].