Computers and Geotechnics 91 (2017) 17–26

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Soil-water retention behavior of compacted soil with different densities over a wide suction range and its prediction

You Gao, De'an Sun *

Department of Civil Engineering, Shanghai University, Shanghai 200444, China

A R T I C L E I N F O

Article history:
Received 23 December 2016
Received in revised form 21 June 2017
Accepted 25 June 2017

Keywords:
Unsaturated soil
Wide suction range
Soil-water retention curve
Density effect
Air entry value
Residual suction value

A B S T R A C T

To investigate the soil-water retention behavior of a clayey silt over a wide suction range, the suction is imposed on clayey silt specimens using the pressure plate method and vapor equilibrium technique with saturated salt solutions. The test results show that the soil-water retention curves (SWRCs) in terms of gravimetric water content versus suction relation over a wide suction range are independent of the initial dry density or void ratio when the suction is higher than a specific value, which can be determined by results of the mercury intrusion porosimetry test. When the SWRC is expressed in terms of degree of saturation versus suction relation over a wide suction range, the influence of dry density or void ratio is highlighted. This behavior can be explained by the features of the pore-size distribution. Residual suction and water content of specimens with different void ratios are almost the same and the air entry values of specimens show a linear relationship in the plane of water content versus suction with the logarithmic coordinate. Finally, the Fredlund and Xing SWRC equation is used to uniformly describe the SWRCs of specimens with different void ratios by taking above features of the SWRC into consideration, and the predicted results are compared well with measured values.

1. Introduction

The soil-water retention curve (SWRC), which represents a soil's ability to store and release water as it is subjected to various soil suctions, is defined as the relationship between the suction and the degree of saturation or the gravimetric water content for unsaturated soils [1]. The soil-water retention behavior is fundamental to a comprehensive understanding of the water flow, deformation processes, and shears strength for unsaturated soils. Therefore, the soil-water retention behavior is important for many applications in geotechnical engineering.

The SWRC of soils depends on several factors, such as soil type (e.g., [2–4]), soil structure (e.g., [5–7]), temperature (e.g., [8–10]), salt content (e.g., [11,12]) and stress states (e.g., [2,5]), etc. These factors can be classified into two groups: internal and external factors. Internal factors are those related to the soil type and soil structure, such as mineralogical composition, pore size distribution and bonding (i.e., chemo-physical properties of the soil phases). Typical external factors are stress states and temperature. For the same type of soil, the effect of stress states on the SWRC can be attributed to the effect of the density change. Sun et al. [13] have reported that the SWRC expressed by the relation between the suction and degree of saturation depends mainly upon the current density and not directly upon the stress state. Therefore, one important factor that affects the SWRC is the density. It is worthwhile to investigate the effect of density on the SWRC, especially over a wide suction range. For example, Romero et al. [14] analyzed main wetting and drying data of Boom clay with two densities by the axis translation technique and vapor equilibrium procedures in the suction range about from 0.01 to 200 MPa. Birle et al. [15] investigated the effects of the initial water content and dry density of a compacted Lias-clay on the SWRCs in the suction range from 1 to 200 MPa. Salager et al. [16] studied the influence of water retention behavior of deformable soils with different densities in the suction range from 0.01 to 300 MPa. The literatures mentioned above just simply analyzed the macro phenomenon of the soil-water retention behavior over a wide suction range. However, the basic parameters (such as air-entry value, residual suction, and slope at the transition zone) of SWRC and the soil microstructure requires a comprehensive analysis, which can lead to a better understanding of the soil-water retention behavior over a wide suction range. Such as, Khalili et al. [17] proposed a fully coupled constitutive model for describing the volumetric deformation of water and air phases that provides a platform to relate the hydraulic functions to the mechanical status of unsaturated soils.

* Corresponding author at: 99 Shangda Road, Shanghai 200444, China.
E-mail address: sundean@shu.edu.cn (D. Sun).

http://dx.doi.org/10.1016/j.compgeo.2017.06.016
0266-352X/

Pasha et al. [18] presented a model for the evolution of main and scanning curves due to loading and change in the hydraulic path as well as the SWRC parameters such as air entry value, pore-size distribution index and slope of the scanning curve.

The water retention behavior is strongly affected by not only void ratio but also pore structure. Simms and Yanful [19] analyzed the evolution of soil microstructure during the SWRC tests for a compacted clayey soil. Romero et al. [20] proposed a model by taking into account the evolution of the aggregates size during the wetting and drying processes. Zhou and Ng [21] developed a simple water retention model by considering the stress effects on void ratio as well as the pore structure. It is well recognized that the soil microstructure plays a decisive role in its soil-water retention behavior. The soil microstructure can be simply represented by the pore-size distribution (PDS), which can be determined by Mercury Intrusion Porosimetry (MIP) tests. Therefore, it is worthwhile to do a comprehensive investigation on the effect of density and PDS on the soil-water retention behavior over a wide suction range.

This paper presents a systematical study to investigate the effect of soil density on the SWRC over a wide suction range. To realize the wide suction range, the high suction (3.29–367 MPa) was imposed on the soil specimens by the vapor equilibrium technique and the low suction (0–1500 kPa) was imposed by the axis translation technique. In addition, a comprehensive analysis of the features of SWRCs was made over a wide suction range. Based on the features of the SWRCs with different densities over a wide suction range, the parameters of the equation proposed by Fredlund and Xing [22] can be determined. Finally, a method is proposed to describe the SWRCs of specimens with different densities during drying over a wide suction range.

2. Testing technique

To measure the hydro-mechanical behavior of unsaturated soil in a wide range of suction, two different techniques were used for suction control. For suctions ranging from 1 to 1500 kPa, the axis translation technique was adopted in the pressure plate device, i.e., the pressure plate method (PPM). For suctions ranging from 3 to 367 MPa, the suction was applied by means of the vapor equilibrium technique (VET) with saturated salt solutions in desiccators.

2.1. Pressure plate method

The pressure plate device for measuring the SWRC, which is equipped with 5-bar and 15-bar high air entry (HAE) ceramic discs and 1.5-MPa apressurizer. It is designed based on the axis translation technique, which directly controls matric suction by increasing air pressure while maintaining the pore-water pressure in specimens equal to atmospheric pressure.

2.2. Vapor equilibrium technique

VET is commonly employed to control high suctions for unsaturated soil tests (e.g., [23–25]). The VET uses chemical solutions, such as saturated salt solutions, to generate constant total suction conditions in a closed space (such as a sealed container). The potential of the chemical solution forces the water potential in the closed space and that in the soil sample to reach equilibrium. Greenspan [26] collected reference data for the values of relative humidity of different saturated salt solutions and corresponding suctions, as listed in Table 1. The testing procedure adopted for the VET was explained in detail by Sun et al. [7], and the volume of irregular soil samples was measured using the fluid paraffin replacement technique (e. g., Peron et al. [27]).

Table 1
Saturated salt solution and corresponding suction (20 °C).

Saturated salt solution	*RH%*	Total suction (MPa)
LiBr	6.6	367.54
$MgCl_2$	33.1	149.51
NaBr	59.1	71.12
KI	69.9	48.42
NaCl	75.5	38.00
KCl	85.1	21.82
KNO_3	94.6	7.48
K_2SO_4	97.6	3.29

2.3. Material and sample preparation

The soil used in this study is a clayey silt called Pearl clay, which has a liquid limit of 43% and a plasticity index of 17.5 by the combining test of liquid and plastic limits, and specific gravity of 2.71. The hydraulic conductivity of Pearl clay with an initial void ratio of 1.1 is about 1.58×10^{-6} cm/s. Fig. 1 shows the grading curve of Pearl clay. It can be seen from Fig. 1 that the soil is composed of 26% clay fraction (<2 μm) and about 74% silt fraction. The clay mineralogy compositions, determined using the X-ray diffraction test, include quartz, pyrophyllite, and kaolinite in the dominant order. There is little expansive clay mineral in Pearl clay.

The size of specimens for the pressure plate method and vapor equilibrium technique is 20 mm in height and 61.8 mm in diameter. Compacted specimens were prepared by compacting the soil sample in a mould at gravimetric water content of about 26%, obtained by spraying water over the dry powdered Pearl clay uniformly. The compacted specimens were prepared by static compaction in a stainless steel specimen ring with 61.8 mm inside diameter and 20 mm height. The physical property indexes of specimens after preparation and saturation are list in Table 2.

3. Test results and discussions

3.1. Effect of density on SWRC over wide suction range

Fig. 2 shows the measured SWRCs with the changes in gravimetric water content (w) and degree of saturation (S_r) with suction in the drying tests at the initial moulding void ratios of about 1.36, 1.24 and 1.10 (as shown in Table 1) using the pressure plate method. In Fig. 2, it can be seen that the air-entry values of the

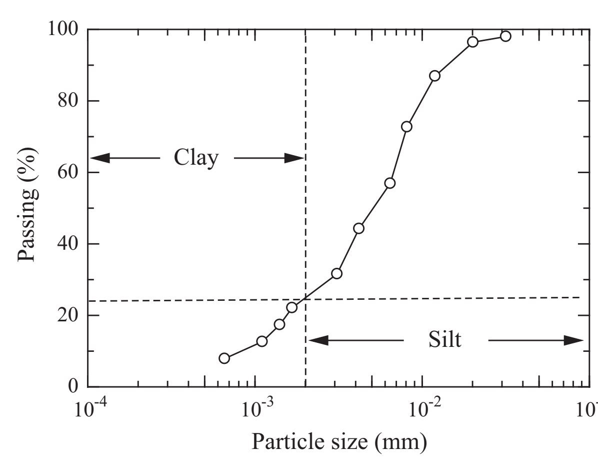

Fig. 1. Grading curve of Pearl clay.