TRANSACTIONS
OF TIANJIN UNIVERSITY

2016, 22: 268-272
DOI 10.1007/s12209-016-2744-5

Influence of Dry Density on Soil-Water Retention Curve of Unsaturated Soils and Its Mechanism Based on Mercury Intrusion Porosimetry*

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Abstract: The soil-water retention curve（SWRC）can be used to evaluate the ability of unsaturated soils to attract water at various water contents and suctions. In this study, drying SWRCs for a kind of sandy soil were obtained in the laboratory by using self-modified SWRC apparatus. In addition, the porosity and the pore size distribution of the samples were investigated by a mercury porosimetry test in order to analyze the effect of dry density. Results showed that the soil-water retention of the soil specimens was strongly dependent on the dry density. Under zero suction, soil specimens with a higher dry density exhibited lower initial volumetric water content. The higher the dry density of soil, the more slowly the volumetric water content decreased with the increase of suction. There was a general and consistent trend for a soil specimen to possess a larger air-entry value and residual suction, while smaller slope of SWRC when it had a higher density. This was probably attributed to the presence of smaller interconnected pores in the soil specimen with a higher dry density. The proportion of large diameter pores decreased in comparison to pores with small diameters in the soil tested. The measured total pore volume of the soil specimen, which had a larger dry density, was lower than that of the relatively loose specimens.

Keywords: soil-water retention curve; dry density; mercury intrusion porosimetry; unsaturated soil

Various geotechnical engineering problems involving unsaturated soils can be classified into three general phenomena: flow, stress, and deformation. Most practical engineering problems involve all the three phenomena simultaneously. Soil-water retention curves（SWRCs）fall into the class of flow phenomena, which are mainly categorized as capillary flow and are also indirectly used to solve problems related to other phenomena. Therefore, SWRCs play an important role in understanding the behavior of unsaturated soils, and they have been used to estimate the hydraulic conductivity, shear strength, and volume change of unsaturated soils [1-6].

SWRC, typically a sigmoid, illustrates the relationship between the suction and water content of soil. Factors affecting the SWRCs of soils have been researched, such as stress state[7, 8], temperature[9-11], grain-size distribution[12,13], and dry density[14]. Any of these previous studies did not investigate quantitatively the influence of density on the SWRCs. Therefore, it is important to conduct such a quantitative investigation to enhance the predictive methods of the SWRCs. In this study, drying SWRCs for a kind of sandy soil were obtained in the laboratory by using self-modified SWRC apparatus. The influence of the dry density of the soil on SWRCs was then discussed. In addition, the porosity and the pore size distribution of the samples were investigated by a mercury porosimetry test in order to analyze the effect of dry density.

1 Experimental methodology

1.1 Test materials

In this study, a kind of sandy soil was employed as the test material. Physical properties and grain size distribution curve for the test specimens are shown in Tab. 1 and Fig. 1, respectively. This soil was classified to be

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Accepted date: 2015-09-29.
*Supported by the National Natural Science Foundation of China（No. 51409261）.
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silty sand in accordance with the Unified Soil Classification System using JGS (Japanese Geotechnical Society) standard test method.

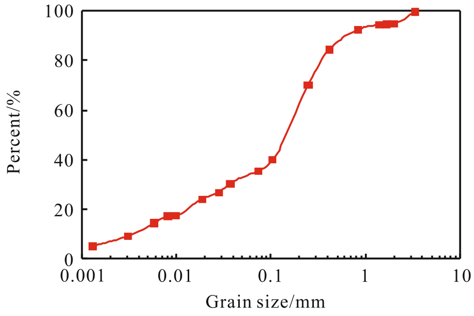


Fig. 1 Grain size distribution curve for test material

Tab. 1 Physico-mechanical properties of soil

Property	Value	Property	Value
G_s	2.75	e_{min}	1.11
D_{10}/mm	0.003 5	w_L/%	25.78
D_{50}/mm	0.14	w_P/%	23.52
C_u	54.40	I_P	2.26
C_c	1.95	w_{opt}/%	17.56
e_{max}	1.74	$\rho_{d,\max}$/(kg·m^{-3})	1 700

1.2 Test apparatus

A triaxial apparatus was modified for the measurement of SWRC under constant total stress conditions. Schematic illustration of the test setup is shown in Fig. 2. The apparatus comprised of base pedestal embedded with a circular shaped ceramic disk (air-entry value $\varphi_a = 300$ kPa). Specimens (75 mm in diameter and 41 mm in height) were prepared inside a latex membrane which was supported by a brass split mold. Water flowing into or out of the specimen was established by monitoring the weight of a water bottle connected to saturated ceramic disk. The water bottle was placed on a weighing balance and a camera took photos of its readings at regular time intervals. For more detail, see Ref. [15].

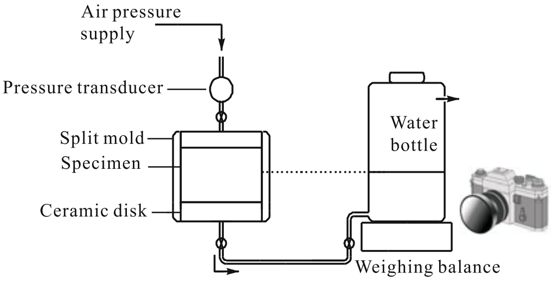


Fig. 2 Schematic layout of modified SWRC apparatus

1.3 Specimen preparation

The experimental procedures broadly involved ceramic disk saturation, sample preparation, and obtaining SWRC.

Soil samples with dry density of 1.30, 1.40, 1.50 and 1.60 g/cm^3 were used in this experimental program. Soil was mixed with water to attain gravimetric water content of 10% for all experiments. Water connection to ceramic disk was open to make specimen saturated.

1.4 Determining SWRC

For the determination of SWRC during drying and wetting, the saturated soil specimen was subjected to various magnitudes of matric suction. As the matric suction increased, water was expelled from the soil specimen into the water bottle. The weight of water expelled was measured to determine the volumetric water content at equilibrium. Each matric suction value was maintained until the equilibrium condition was reached. In this study, maximum matric suction applied to the specimen was 200 kPa because of the limitation of the air-entry value of ceramic disk.

1.5 Mercury intrusion porosimetry test

Mercury intrusion porosimetry (MIP) is a powerful technique utilized for the evaluation of porosity, pore size distribution, and pore volume (among others) to characterize a wide variety of solid and granular materials. The porosity of a material affects its physical properties and, subsequently, its behavior in its surrounding environment. The adsorption, permeability, strength, density, and other factors influenced by a substance's porosity determine the manner and fashion in which it can be appropriately used. The instrument, known as a porosimeter, employs a pressurized chamber to force mercury to intrude into the voids in a porous substrate. As pressure is applied, mercury fills the larger pores first. As pressure increases, the filling proceeds to smaller and smaller pores. Both the inter-particle pores (between the individual particles) and the intra-particle pores (within the particle itself) can be characterized with this technique. The schematic of mercury intrusion porosimetry is shown in Fig. 3. The pore size distribution was measured by MIP with an AutoPore Ⅳ apparatus ($p_{max} = 400$ MPa), allowing the investigation of pore radii ranging from 3.7 nm to 1 000 μm. By measuring the volume of mercury that intruded into the sample with each pressure change, the volume of pores in the corresponding size class was calculated. A key assumption in MIP is the pore shape. The method assumes a cylindrical pore geometry by using a modified Young-Laplace equation which was generally referred to as the Washburn equation[16]. The samples for the MIP test were carefully trimmed into pieces having an approximately cubic shape and a volume of about 1 cm^3, and were dried under vacuum by lyophilisation using a Freeze Dryer apparatus (ALPHA 1-2 Ld Plus-Martin Christ Gefriertrocknungsanlagen GmbH) in order to remove the pore water without damaging the original texture of the soil sample. MIP test was conducted on the soil after the end of SWRC test.

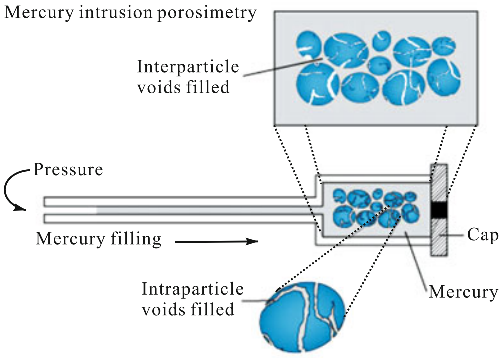


Fig. 3 Schematic of mercury intrusion porosimetry

2 Experimental results

The experimental data of the test material with different densities are shown in Fig. 4 in logarithmic scale. The drying SWRCs obtained in the laboratory are different from each other due to the influence of the dry density. The differences of the SWRCs are determined by the differences of the SWRC parameters such as air-entry value (ψ_a), residual suction (ψ_r), and the slope of SWRC (s). In order to observe the influence of the initial density on the SWRC parameters, the drying SWRCs of soil obtained in the laboratory with different dry densities are considered.

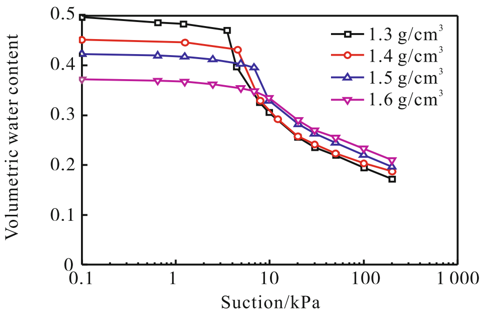


Fig. 4 Influence of dry density on the soil water retention curve during drying

The air-entry value, AEV or ψ_a, is defined as the matric suction at which air first enters the largest pores of the soil during a drying process [17]. As matric suction is increased from zero to the air-entry value of the soil, the volumetric water content of the soil is nearly constant. Then the water content steadily decreases to the residual water content, θ_r, as matric suction increases beyond the air-entry value. The residual water content is the water content at residual state, at which water phase is discontinuous. The soil suction corresponding to the residual water content is called the residual soil suction, ψ_r. The definition of air-entry value (ψ_a), residual suction (ψ_r), and the slope of SWRC (s) is given by Vanapalli *et al*[18]. The slope of the SWRC can be measured as $[(\psi_a - \psi_r)/(\lg\psi_r - \lg\psi_a)]$.

The initial dry density of the soil specimens has some significant influence on the soil-water retention curve, as shown in Fig. 4. Under zero matric suction condition, soil samples with higher dry density have lower initial volumetric water content. The reduction in initial volumetric water content can be attributed to the decrease of void volume associated with the increase of dry density. The volumetric water content of all samples decreases due to matric suction. The rate of drying extremely depends on the dry density. An increase in the dry density of the specimens gives rise to a decrease in the reduction rate of volumetric water content. The air-entry value is defined as the point where the volumetric water content starts to decrease significantly (i.e., the point where the soil gives up water with the increase of soil matric suction).

Fig. 4 shows there is a general tendency for the soil sample having a higher dry density in possession of a larger air-entry value. This is probably due to the presence of a smaller average pore size distribution in the soil sample as a result of higher dry density. Following the procedures proposed by Vanapalli *et al*[18], the air-entry values estimated from each specimen are plotted against dry density in Fig. 5. It can be seen that the air-entry value increases with dry density.

As shown in Fig. 4, the specimen with high density desaturates at a slower rate than that with low density. Fig. 6 indicates the variation of the slope of SWRC with dry density. It can be seen that the dry density rise decreases the slope of SWRC. As a result, the high-density specimens have higher water content than the low-density specimens at matric suction beyond their air-entry values (see Fig. 4).

The residual suction is plotted against the dry density of soil sample and the result is shown in Fig. 7. As Fig. 7 depicts, a rise in initial dry density increases the residual suction. The variation of residual suction against dry density satisfactorily resembles a second-order polynomial. These results are consistent with the findings of Croney and Coleman[19].

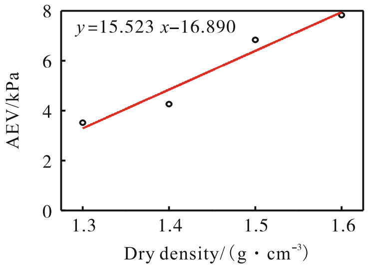


Fig. 5 Variation of air-entry values against dry density

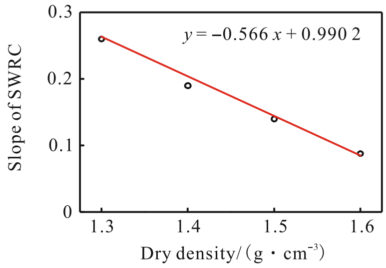


Fig. 6 Variation of slope of drying SWRC against dry density

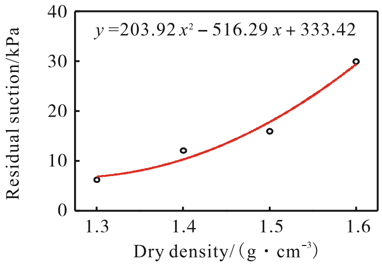


Fig. 7 Variation of residual suction against dry density

3 Soil fabric: pore size distribution

The main changes in the SWRCs result from the pore size distribution of soils, which is confirmed by the mercury porosimetry test. Fig. 8 shows the pore size distribution of samples for soils with different dry densities after the end of SWRC test. Comparing the results of soil materials under different dry density conditions, the main observation is that the pore size distribution changes with dry density, i.e., the proportion of large diameter pores decreases in the soil tested. The measured total pore volume is lower for the soil specimen having larger dry density as compared to the relatively loose specimens. These results indicate that a connection exists between the decreased volume of larger pores caused by dry density and SWRC.

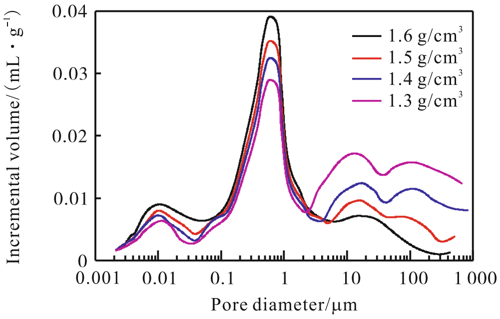


Fig. 8 Effect of dry density on the pore size distribution of the soils

4 Discussion

In unsaturated soils, the existence of water creates surface tension which bonds soil particles. This bond is quantified as matric suction. In other words, water gives a tension act depicted by a meniscus between two solid particles (see Fig. 9).

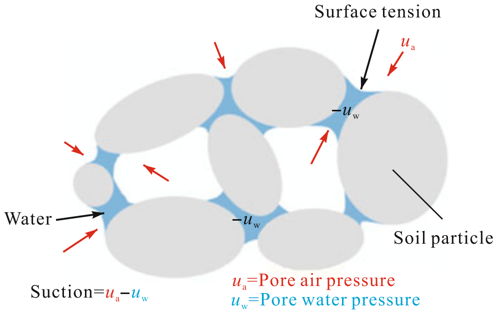
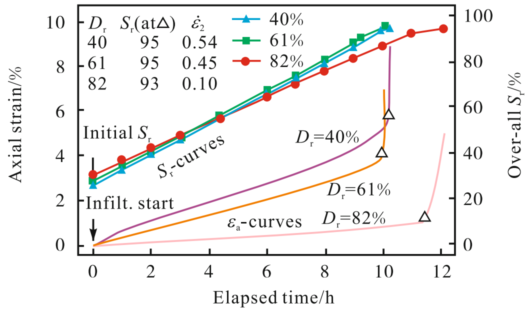


Fig. 9 Condition of soil structure

In order to observe the effect of initial relative density (D_r), Farooq *et al*[20] and Orense *et al*[21] conducted a comprehensive study using three different materials, namely sand, silty sand and gravelly sand, in a modified triaxial drained apparatus. Specimens were subjected to constant shear stress to represent slope condition, and water was injected into the specimens to represent rainfall. In those tests, the pore water pressure was measured by miniature sensor which responded only to positive pressure. Fig. 10 shows the response of sand to various relative densities. From the test it was observed that the specimens failed after the development of pore water pressure. Loose specimens experienced a higher strain rate after failure initiation, while denser specimens had a



Kumano-silty sand σ^3=25 KPa
△—Failure initiation
$\dot{\varepsilon}_2$—Strain rate after △(%/min) K=2.5

Fig. 10 Effect of specimen's relative density (D_r) during failure under water infiltration[20] lower strain rate. Low initial matric suction of loose specimens can dissipate quickly after the injection of water. Hence, loose specimens tended to lose their strength more rapidly and initiate failure occurred earlier than dense specimens.

5 Conclusions

(1) Under zero suction, soil specimens with a high dry density exhibit low initial volumetric water content. There is a tendency to change the volumetric water content at a slow rate as the values of suction increase for the soil with a high dry density.

(2) There is a general and consistent trend for a soil specimen to possess a large air-entry value and residual suction, while a small slope of SWRC when it has a high density. This is probably attributed to the presence of small interconnected pores in the soil specimen with a high dry density.

(3) The proportion of large diameter pores decreases in the soil tested. The measured total pore volume is low for the soil specimen having a large dry density as compared to the relatively loose specimens.

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(Editor: Zhao Yang)