

Influence of Stress on Soil-water Characteristic Curve of Intact Loess

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Abstract. The soil-water characteristic curve plays a significant role in describing the unsaturated soil characteristics, and is greatly affected by stress state, wetting and drying cycles and other factors. Accurate measurement of soil-water characteristic curve is the key to the unsaturated soil mechanics studies. In this paper, based on the GCTS soil-water characteristic curve (SWCC) instrument, the undisturbed loess was tested to study the effects of one-dimensional consolidation stress, stress history and wetting and drying cycles on the soil-water characteristic curve of undisturbed loess. The experimental results show that: (1) As the one-dimensional axial stress increases, the air intake of the soil sample gradually increases, and the decrease of the water content slows down as the matrix suction increases; (2) Due to the increase of the pre-consolidation stress, soil compactness increases, and pore size reduces, which makes the water migration more difficult. Therefore, as the sampling depth of soil increases, the air intake increases and the residual water content decreases. (3) Due to the pore size, bottleneck effect and contact angle, the water content of the humidification curve is higher under the same matrix suction, and the soil-water characteristic curve in the humidification test shows obvious hysteresis effect.

1. Introduction

Unsaturated soil is a difficult and hot research topic in current soil mechanics research at home and abroad. It is widely distributed in China. When the Loess Plateau of Northwest China is featured by the arid and semi-arid climate with large groundwater depth, the surface loess is generally unsaturated [1]. Unsaturated loess presents many problems in the engineering construction process. Especially, the engineering accidents of unsaturated loess occur frequently in the railway, highway, foundation and slope engineering projects. Unsaturated loess is a three-phase soil [2] and composed of solid phase, liquid phase and gas phase. The presence of gas phase and the change of gas-water ratio lead to different states and engineering properties, which make it more complex than the saturated soil. Its difference from the saturated loess is the presence of matrix suction in unsaturated soil, which is the root cause of the obvious difference in



engineering properties between unsaturated loess and saturated loess. The matrix suction reflects the retention effect of soil matrix featured by loess structure, soil particle composition, pore size and distribution patterns on the water content in the soil, and plays a very important role in controlling the mechanical properties of unsaturated loess. As a result, the matrix suction becomes an important parameter for studying the engineering properties of unsaturated loess [3]. The matrix suction of unsaturated loess varies with the water content. The relationship between water content and matrix suction is referred to as the soil-water characteristic curve, which indicates the relationship between the matrix suction of unsaturated soil and its mass water content, volumetric water content, and saturation.

As unsaturated loess and saturated loess are very different, there are many factors affecting the soil-water characteristic curve, including soil type, mineral composition, structure, initial water content, porosity, and stress history. Specifically, the stress history and initial water content of the soil play a major role in the soil structure, thus controlling the main properties of the soil-water characteristic curve. SK Vanapalli et al. [4] paid attention to this problem at an earlier stage, studied the effects of stress history and soil structure on the SWCC of remolded clay by a series of pressure plate tests and compared the SWCC of samples with different initial porosity. The research shows that soil structure has a significant impact on SWCC patterns. In 2000, Charles W. W. Ng and Y. W. Pang [5] used the one-dimensional consolidation volume pressure plate to test the SWCC of Hong Kong residual soil in K0 state, and believed that the variation range of volumetric water content decreases gradually with the axial stress increases, and that a greater axial stress corresponds to a higher air intake of the soil. Biwei Gong [6, 7] used the volumetric pressure plate to conduct experimental research on the change characteristics of suction and strength during the wetting and drying cycles of expansive soil, and considered that the stress state has a significant impact on the soil-water characteristic curve of expansive soil. Zhiqing Li et al. used the unsaturated soil triaxial instrument to conduct experimental research on the soil-water characteristic curve of expansive soil, analyzed the impacts of porosity ratio and consolidation stress, fitted and compared the soil-water characteristic curve by indoor and outdoor suction force measurement, and finally established a power function model [8]. Shimei Wang et al. used the unsaturated direct shear instrument to measure the relationship between water content and the consolidation stress, and pointed out the properties of soil-water characteristic curve related to the consolidation stress [9]. Shangzhi Mao compared the test results of the soil-water characteristic curves in the dialysis technique and the axis translation technique, and analyzed the impacts of stress and suction force history on the soil-water characteristic curve [10]. Linchang Miao et al. conducted an experimental study on the water content characteristics of Nanyang expansive soil, and analyzed the impacts of pre-stress on the water content characteristic curve in the wetting and drying cycles [11]. For a long time, the researches on unsaturated loess focus on the relationship of matrix suction with water content and saturation, or the impacts of soil particle composition and porosity on soil-water characteristic curve. However, few researches investigate the impacts of stress state on soil-water characteristic curve. Therefore, the pressure plate instrument is used to test the impacts of one-dimensional consolidation stress, soil sampling depth and wetting and drying cycles on the soil-water characteristic curve of unsaturated loess in order to obtain more accurate test data, and lay a good foundation for understanding and predicting the engineering properties of unsaturated soil in the Loess Plateau.

2. Test equipment and plan

Accurate measurement of high matrix suction is one of the main difficulties in current unsaturated soil mechanics tests. The axis translation technique proposed by Hilf in 1956 is adopted in this study. Due to its clear technical concept, simple equipment, and convenient suction control and application, it has been widely used. The axis translation technique is suitable for the double open state in which the water and vapor are connected. The magnitude of the matrix suction applied to the soil sample by the axis translation technique mainly depends on the air intake of the ceramic plate, which is usually within 1500kPa. At present, a variety of test techniques and instruments for matrix suction have appeared at home and abroad. The most common direct measurement methods are the tension gage method and the pressure film meter. In 2005, GCTS and Professor Fredlund jointly developed a consolidation instrument based on the axis translation technique, which is capable of testing continuous and complete soil-water characteristic curves under a certain net normal stress state. As shown in Fig. 1, the instrument consists of two main components: a pressure chamber and a loading system. The pressure chamber is made of stainless steel and can

withstand large air pressure; the soil sample is prepared by cutting ring, and placed on the saturated ceramic plate during the test; the ceramic plate with different air intakes (5 bar, 15 bar) is suitable for different soil samples. The ceramic plate with high air intake can be embedded in the circular groove at the base of the pressure chamber. The bottom of the pressure chamber is a connected serpentine groove for communicating the volumetric tube and the water in soil sample, and also for washing away the bubbles in the water. The change of water volume in the two volumetric tubes can be used to calculate the change in the water content of the sample, and the accuracy of the volumetric tube is 1mm.



Figure 1. GCTS SWCC instrument photo.

The samples are taken from the undisturbed loess in Pingliang, Tianshui and Dingxi of Gansu. The basic physical and chemical parameters of the samples are shown in Table 1. The test plan is shown in Table 2.

Table 1. Physical parameters of soil samples.

Numbre	Sample No.	Depth/m	Density/g/cm ³	Dry Density/g/cm ³	Water Content/%	Porosity	Grain size composition /%			plasticity index
							sand	silty	clay	
1	TSBYC	5 m	1.64	1.46	12.5	0.46	10.0	66.5	23.5	8.5
2	TSDJZ	4 m	1.42	1.30	9.6	0.52	10.3	73.5	16.2	11
3	DX-1	4 m	1.57	1.34	17.3	0.51	--	--	--	--
4	DX-2	6 m	1.57	1.34	17.4	0.51	7.0	73.5	19.5	10.7
5	DX-3	8 m	1.56	1.33	17.2	0.51	--	--	--	--
6	PL	6 m	1.50	1.30	15.3	0.52	--	--	--	8.9

Table 2. Test plan.

Sample No.	Test method and purpose
DX ₁ —DX ₃	Impacts of different one-dimensional consolidation stresses on the soil-water characteristic curve
DX ₁ —DX ₃	Impacts of (stress history) soil sampling depth on the soil-water characteristic curve
PL, DX ₁ ,	Impacts of humidification test and dehumidification test on the soil-water characteristic curve
TSBYC	Impacts of wetting and drying cycles on the soil-water characteristic curve

3. Impacts of stress state on the soil-water characteristic curve

3.1. Impacts of one-dimensional consolidation stress

The study of soil-water characteristic curve has been carried out for a long time at home and abroad, but mainly focuses on experimental research and mathematical simulation and rarely considers the impacts of different influencing factors on the curve. For example, as the soil has a certain stress history, it is necessary to consider the impacts of different consolidation stresses and vertical loadings on the curve.

As shown in Fig. 2, the dehumidification test process is as follows: Impose a one-dimensional consolidation stress (namely K_0) on the soil sample by the vertical loading system to simulate the overburden stress of the actual soil layer (namely the net normal stress); select the undisturbed DX loess sample, first saturate the sample, then conduct the dehumidification test, and apply the axial consolidation stresses of 0kpa, 100kpa and 200kpa respectively through the vertical loading system, and apply the first stage air pressure after the consolidation is stabilized; then, after the water and air reaches a stable balance, flush and record the displacement, apply the next stage air pressure ; repeat the above cycle until the predetermined air stress is reached, remove the load, take out the sample and measure the water content to obtain the soil-water characteristic curve. The soil sample with higher one-dimensional consolidation stress has a larger air intake, but its decrease rate of water content slows down as the matrix suction increases. This is also because a larger consolidation stress makes the soil sample more compact and reduces the pore size.

There is another impact of one-dimensional consolidation stress on the sample. When vertical stress is applied to the sample, a matching loading plate is required to transfer the vertical stress to the sample. The loading plate has a diameter of 45mm and slightly smaller than 50mm ring cutter. During the dehumidification test, the loading plate transfers the load to the saturated soil sample and the water in the sample is squeezed out of the ring cutter. The loess will also overflow onto the ceramic plate with the water, the sample volume changes and the loading plate will be stuck with the sample, which affects the accuracy of the test results. There is no such problem in the humidification test when the water content of the sample is low. Once the water content rises to a certain value, the soil sample overflows. In order to reduce the error caused by this phenomenon during the test, the total weight of the ceramic plate, sample, ring cutter and loading plate should be weighed together to obtain m_1 . Then, the soil sample is taken to the weighing box to measure the residual water content; then the ceramic plate, ring cutter and loading plate are washed, and then weighed to obtain m_2 . Therefore, the weight of the soil sample after the test is $m_1 - m_2$.

3.2. Impacts of stress history on the soil-water characteristic curve

As shown in Table 1, the soil samples taken at different depths at the same location of DX show similar physical properties. Different depths represent different stress histories of soil samples. The stress history of soil plays an important role in the structural formation of soil. Air intake refers to the corresponding matrix suction when the air begins to enter the maximum pores between the soil particles or the aggregate of particles; residual water content refers to the critical water content when the water content in the soil decreases to a certain value as the suction force increases, the continued reduction of the water content requires a large suction force.

The relevant research pointed out that the air intake of the soil sample increases as the pre-consolidation stress increases, but the dehydration rate decreases because a larger pre-consolidation stress makes the soil sample more compact and reduces the pore size, which makes the water migration more difficult. As shown in Fig. 3, the three soil-water characteristic curves are arranged very regularly. First, as the depth increases, the transformation section of the soil-water characteristic curve is steeper, which means that as the depth increases, the air intake increases. Second, the soil-water characteristic curves are arranged from top to bottom in the order of depth, which means that as the depth increases, the residual water content decreases.

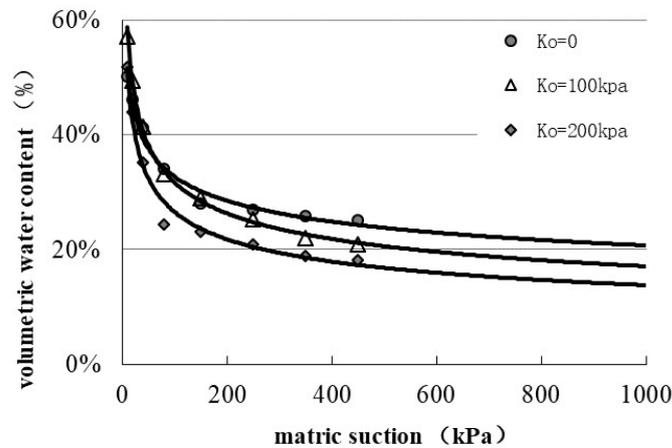


Figure 2. Effect of one-dimensional consolidation stress on SWCC (DX).

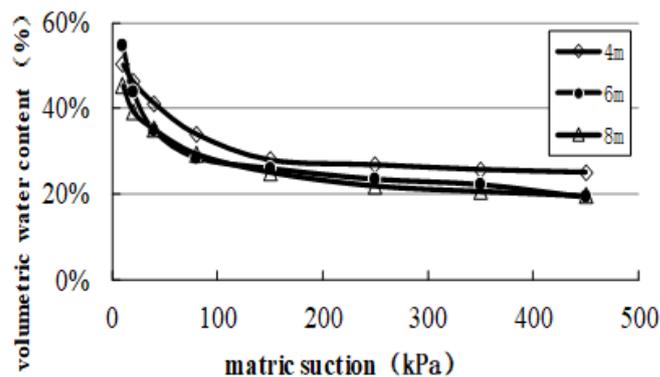


Figure 3. Effect of depth stress on SWCC (DX).

4. Impacts of wetting and drying cycles on the soil-water characteristic curve

At present, the dehumidification process in the unsaturated soil-water characteristic curve is the research focus of the curve. However, the change in the water content of unsaturated soil in actual engineering is very complicated, and the water content often changes with different seasons and weather. Therefore, it is necessary to focus on the cyclical changes of the dehumidification process and the humidification process of the soil-water characteristic curve.

There are two test methods for measuring soil-water characteristic curves by Fredlund Soil Water Analyzer: dehumidification test and humidification test. Dehumidification test means that the soil sample is saturated by a certain method, and then placed in the pressure chamber, and the air pressure is applied from the minimum to the maximum to discharge the water in the soil sample. Then, the volumetric tube readings under each level of air pressure after the balance are recorded, thereby obtaining the soil-water characteristic curve. The humidification test is just the opposite. First, the test sample is dried and placed in the pressure chamber. Then, the air pressure is applied from the maximum permitted air pressure on the ceramic plate to make the soil sample absorb water, and reduce the bending liquid level in the volumetric tube. Finally, the volumetric tube readings under each level of air stress after the balance are recorded, thereby obtaining the soil-water characteristic curve. In order to study the impacts of the wetting and drying cycles on the soil-water characteristic curve, three tests are carried out. In two tests, 2 cutting-ring samples are made by the PL 6m and DX 4m loess, one for dehumidification test and one for humidification test; in the last test, a TSBYC5m soil sample is prepared, placed in the pressure chamber, first saturated for dehumidification test, and then for humidification test. The soil sample is always kept in the pressure chamber during the tests. In order to reduce the test error, the air pressure of each level applied is the same,

and the balance time is consistent. The soil-water characteristic curve obtained by the test is shown in Figures 4-6.

Figures 4 and 5 show the soil-water characteristic curves obtained by the dehumidification and humidification tests of loess at the same sampling depth (6m and 4m) at the same location (PL and DX). The dehumidification curve is lower than the humidification curve, which means that under the same matrix suction force, the water content of the humidification curve is higher, and there may be two reasons: the first is that the air pressure in the humidification curve is applied from the maximum to the minimum, and the attenuation effect of the air pressure on the instrument is immediate, but the stress attenuation in the soil sample requires a process. However, there is no such problem in the dehumidification curve; the second is that as the stabilization time for air pressure of each level in the humidification test and the dehumidification test is the same, it takes longer for the humidification test to reach the water-gas balance state. Therefore, the balance is not reached when the water content is read.

The loess dehumidification/humidification cycle of TSBYC5m shown in Figure 6 constitutes a relatively obvious hysteresis loop. The humidification curve is obviously lower than the dehumidification curve, which means that SWCC has obvious hysteresis effect, and that the water content in soil is not only determined by the current suction force but also closely related to the change history of suction force. For example, the water content corresponding to the same suction force on the dehumidification curve is higher than that on the humidification curve. The suction force alone cannot accurately describe the impacts of water content on the hydraulic and mechanical properties. Instead, the hysteresis effect should be considered in the simulation of the hydraulic and mechanical properties of soil.

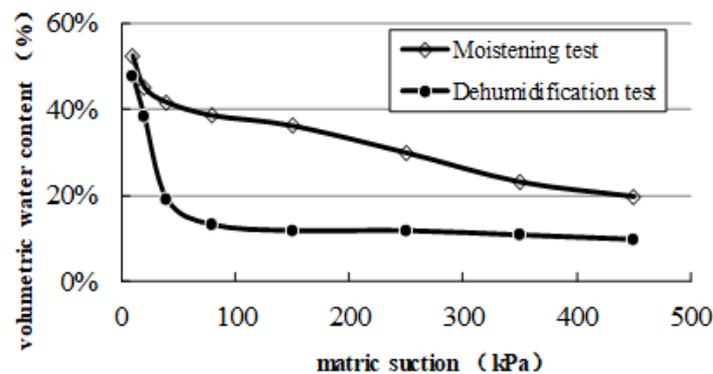


Figure 4. SWCC of intact loess in PL city (6m).

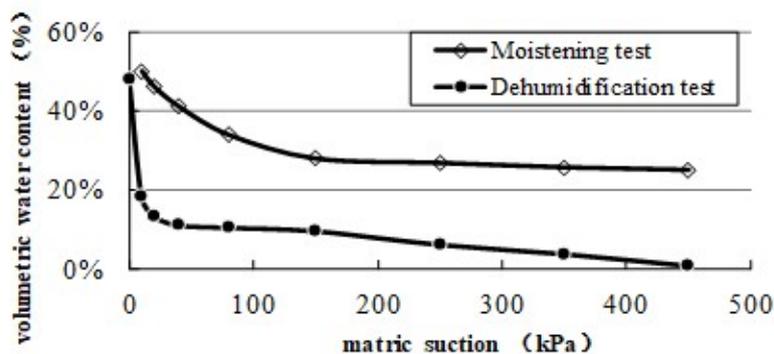


Figure 5. SWCC of intact loess in DX city (4m).

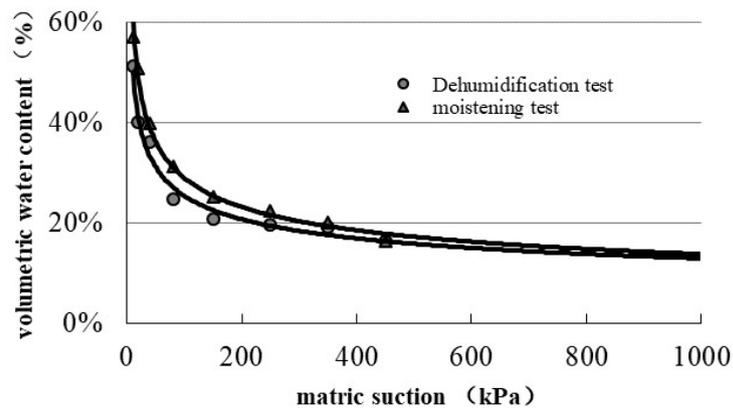


Figure 6. SWCC of intact loess in TSBYC county (5m).

Klausner (1991), and Fredlund et.al (2000) summarizes the causes of the hysteresis effect of the soil-water characteristic curve into the following points:

(1) Pore size effect: Due to the uneven pore size in the soil, it is easier for the water to enter or exit the larger pores with better interconnection in the humidification and dehumidification process. But it is relatively difficult for the water to enter or exit the smaller pores. Therefore, the residual water in the small pores in the drying process is more than that in the humidification process, which makes the same suction force corresponding to the water content on the dehumidification curve higher than that on the humidification curve.

(2) The bottleneck effect is caused by the different sized pores and the size difference between the interconnected pore throats: During the humidification process, there is a size difference between the pores and the throat connected to them. Naturally, the pore water faces bottlenecks in the process of influx, which is difficult to break through, and results in the water content at humidification smaller than that at the dehumidification under the same suction force.

(3) Impacts of contact angle: During the drying and wetting process, the contact angle at the water-gas interface is also different. In general, the contact angle is smaller in drying process than in wetting process. A small contact angle corresponds to a large surface tension, and thus the retention energy to water is high. The difference in the size of contact angle determines the difference in the retention characteristics of the water, which is referred to as the rain point effect.

5. Conclusion

(1) The soil-water characteristic curve test with one-dimensional axial loading is performed. The preliminary research shows that as the one-dimensional axial stress increases, the air intake of the soil sample increases, but the decrease rate of water content slows down as the matrix suction force increases.

(2) The impacts of stress history on the soil-water characteristic curve are analyzed, and the soil samples taken at different depths are tested. The results show that as the soil depth increases, the air intake increases and the residual water content decreases. The reason is that a larger pre-consolidation stress makes the soil sample more compact and reduces the pore size, which makes the water migration more difficult.

(3) Through the comparison of the humidification test, dehumidification test and wetting and drying cycles test, it is found that under the same matrix suction force, the water content in the humidification curve is higher because the soil-water characteristic curve in the humidification test demonstrates obvious hysteresis due to the pore size, bottleneck effect and contact angle.

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