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Experimental study on the soil-water characteristic curve of the unsaturated loess in East Gansu province

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In order to study the soil-water characteristic curve (SWCC) of unsaturated loess in East Gansu province, the effects of initial dry density and net mean stress on the SWCC of unsaturated loess were studied by a unsaturated soil triaxial apparatus. The results showed that when the matrix suction was the same, the moisture content of samples decreased with the increase in net mean stress. The larger the initial dry density, the smaller was the moisture reduction rate, and the higher was the final moisture content. Through the Van Genuchten model it was found that the residual moisture content θ_r decreases with the increase in net mean stress; the numerical values of the fitting parameters α and n do not change significantly as the net mean stress increases. The initial dry density mainly has an effect on the parameters θ_r and α of SWCC while the parameter n is not much affected.

Key words: Unsaturated loess; Soil-water characteristic curve; Matrix suction; Initial dry density; Net mean stress; VG model parameters

INTRODUCTION

As important as the research on consolidation curves in saturated soil mechanics, SWCC research is considered significant for explaining the character of unsaturated soils, subject to which the characteristics of permeability, deformation and strength and many mechanical model parameters of unsaturated soils are determined [1]. According to modern soil mechanics, the SWCC and its mathematical model are some of the constitutive relations of unsaturated soils [2-4]. Therefore, many scholars have made a large number of studies on the SWCC of unsaturated soils with the concept, theory and method based on which the constitutive relation is studied, and explained some characteristics of unsaturated soils in depth using SWCC. From a broad point of view, a SWCC refers to a curve that considers the effect of stress path and state [5].

In the research on the SWCC of unsaturated soils, many scholars have paid attention to the factors that influence the SWCC of unsaturated soils and made related research, obtaining many valuable achievements. Vanapalli *et al*. [6] made experiments on SWCC under different confining pressures of sandy soils of different water contents; by summarizing the results of the research made by the scholars including Black, Mitchell, Fleureau and Avalle, Zhang [7] discovered the rule of change in air-entry value, residual volumetric water content and water holding capacity in relation to soils; through experiments under conditions of one-dimensional lateral confinement, Ng *et al.* [8] found that the SWCC hysteresis loop was reduced with the increase in initial compactness of soil. With two kinds of unsaturated loess of different initial dry density, Xu *et al*. [8] analyzed the effect of stress state on SWCC under conditions of non-pressure, pressure equalization, bias, loading and unloading stress.

For economic reasons, previous research was mainly made on the loess of the northwest regions including Lanzhou and Xi'an, but rarely on East Gansu [9-13]. With the further implementation of the national strategy of developing the western region and the Belt and Road incentive, since Qingyang is a pilot sponge city, Eastern Gansu is making efforts to boost the construction of infrastructures, in which case there undoubtedly will be many engineering problems, such as slope stability, landslide, design of bearing capacity of shallow foundations and subgrade filling. However, research is rarely made on the unsaturated loess of East Gansu, and many designs in terms of geotechnical engineering are mainly based on the research on those of Xi'an and Lanzhou as well as the actual experience in engineering, which does not fully conform to the actual situation of Eastern Gansu and will undoubtedly cause many potential

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safety hazards or wastes for local construction. That’s why it is necessary to make systematic and in-depth research on the unsaturated loess of Eastern Gansu so as to provide experimental data and theoretical basis for local constructions [14-16].

To deeply reveal the SWCC of the unsaturated loess of Huangtuyuan in Eastern Gansu, in the present paper a test was made on the SWCC, from a broad point of view, of the unsaturated loess of Huangtuyuan with an unsaturated soil triaxial apparatus.

Test samples, instrument and method

Basic nature of soil samples

The soil samples for the test are taken from a construction site of Qingyang 7~9 m below the ground. As silty clays, the samples have a natural water content of 13.22% and an average natural density of 1.64 g/cm^3, with a plastic limit WP of 17.50% and a liquid limit WL of 29.52%. Refer to Table 1 for the basic physical indicators of the undisturbed samples on the site.

Table.1 Physical indicators of Q3 loess

W (%)	P (g/cm^3)	ρ_d(g/cm^3)	G_S	e	W_L	Wp
13.22	1.64	1.43	2.71	0.895	17.5	29.52

Test instrument

Since the effect of the uniformity of triaxial samples is non-negligible [17], in the paper, special equipment (shown in Figure 1) was used to prepare triaxial samples by the static pressure method to ensure uniform dry density and water content. When the dry density conforms to the design, the test data are more representative.

Fig. 1. Triaxial test apparatus for unsaturated soils and sampling devices

Measuring matric suction is important for SWCC research, but most authors have not considered the stress state and volume deformation of samples in the testing process [18]. The proposed FLSY10-1 stress-strain unsaturated soil triaxial apparatus may be used to study the effect of net mean stress on SWCC, in which the change in volume is considered.

Test method

From a broad point of view, a SWCC refers to a curve that considers the effect of stress path and state [19]. In the paper, the unsaturated soil triaxial apparatus was used to study the effect of net mean stress and initial dry density on SWCC. When the initial dry density was 1.70 g/cm^3, the net mean stress was 50 kPa, 100 kPa and 150 kPa respectively; when the net mean stress was 150 kPa, the initial dry density was 1.50 g/cm^3, 1.60 g/cm^3 and 1.70 g/cm^3, respectively. The test was made on saturated triaxial samples. The detailed method is listed in Table 2.

As both pore air and pore water exist in unsaturated soils and move slowly, it will take a long time to make the pressure of pore air and pore water become stable in the testing process. Considering the weak permeability of unsaturated soils, it is important to establish a standard for sample deformation and drainage stability under the matric suction at each level. According to related studies, the stability is subject to the following standard: the volume of change and water discharge is less than 0.01 cm^3 within 2 h, and it takes no less than 48 h to make the test on matric suction at each level, and such SWCC lasts about one month (the specific period is subject to the final matric suction designed in the test).

Test results and analysis

Effect of net mean stress on SWCC

Since the volume of samples in the SWCC test is variable, the gravitational water content of the samples is not fully linear to the volumetric water content under the matric suction at each level. Particularly, according to ref. [20], if no consideration is given to the change in the volume of soil samples in the test, the volumetric water content obtained using the mass-based water content through the equation of $\theta = (\rho_d / \rho_w) w$ is lower than the actual content, thus increasing the matric suction by about 100 kPa.

Table 2. Test scheme of soil-water characteristic curves

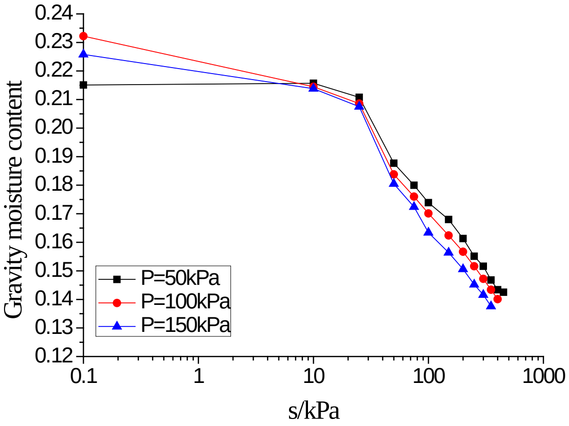
No.	ρ_{sd} / g/cm^3	net mean stress/kPa	matrix suction /kPa
1	1.70	50	0,10,25,50,75,100,150,200,250,300,350,400,450
2	1.70	100	0,10,25,50,75,100,150,200,250,300,350,400
3	1.70	150	0,10,25,50,75,100,150,200,250,300,350
4	1.60	150	0,10,25,50,75,100,150,200,250,300,350
5	1.50	150	0,10,25,50,75,100,150,200,250,300,350

The unsaturated soil triaxial apparatus proposed may be used to directly obtain the variation in the volume of the samples at any time, thus avoiding any error arising from the change in the volume in the testing process. The gravitational water content w_i and the volumetric water content θ_i of the samples under the matric suction at the i^{th} level were calculated as:

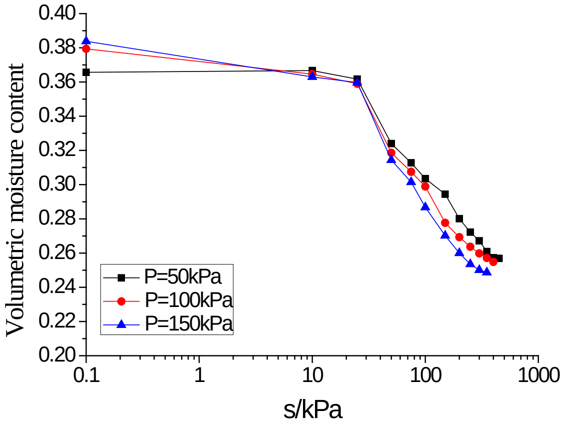
$$w_i = \frac{m_{wi}}{m_s} = \frac{m_{wo} - \Delta m_i}{m_s} = \frac{\rho_d V_o w_o - \Delta m_i}{\rho_d V_o} \tag{1}$$

$$\theta_i = \frac{V_{wi}}{V_i} = \frac{\rho_d V_o w_o - \Delta m_i}{(V_o - \Delta V_i)\rho_w} \tag{2}$$

wherein, V_o and m_{wo} refer to the initial volume and initial water content of the samples, respectively; ΔV and Δm_i refer to the volume of change in and water discharged from the samples under the matric suction at the i^{th} level, respectively.



(a) Presentation with gravity moisture content



(b) Presentation with volumetric moisture content

Fig. 2. SWCC under different net stress

As it takes a long time to make the SWCC test, inevitably, there is a difference between the water discharge measured with the data collection system and the actual discharge. According to the actual water discharge (difference between the initial mass and the mass after the test), a correction was made to the measured value under the matric suction at each level. Considering the error in measuring the water discharge arising out of the environmental factors including temperature next to the drain pipe of the unsaturated soil triaxial apparatus, a drain pipe of the same specification as the pipe was provided to correct for the evaporation of water in the drain pipe in the testing process.

In the test, the gravitational water content *w* and the volumetric water content θ were used to express SWCCs under different net mean stresses. The test result is expressed in a semilog coordinate system as shown in Figure 2.

According to Figure 2, there are some differences between the SWCCs expressed with volumetric water content and gravitational water content, but both present roughly the same form. A SWCC under each net mean stress is divided into 2 different sections based on the demarcation point of the matric suction s which equals 25 kPa. In the first section, the water content slightly changes with the increase in matric suction. This is because the initial water content in the samples is nearly saturated, and the imposed pore pressure u_a is small, making the gas phase in soils suspended in water as closed bubbles and flow with water, in which case the soils are nearly saturated. In the second section, when the matric suction reaches a value (air-entry value of soils), the water content approximately linearly decreases with the increase in matric suction. This is because when air enters the soil and occupies a large pore channel in the soil due to the increase in pore pressure, more water is discharged from the soil with the further increase in air pressure and the water content rapidly decreases, in which case the gas phases in the soil are connected partly and internally. In relation to typical soil-water characteristics, the test result is mainly presented in the first and second sections of the typical SWCC. Due to the limit of the test instrument, the air-entry value of the terracotta panel is 500 kPa, leaving it impossible to measure the residual water content and present the third section of the typical SWCC.

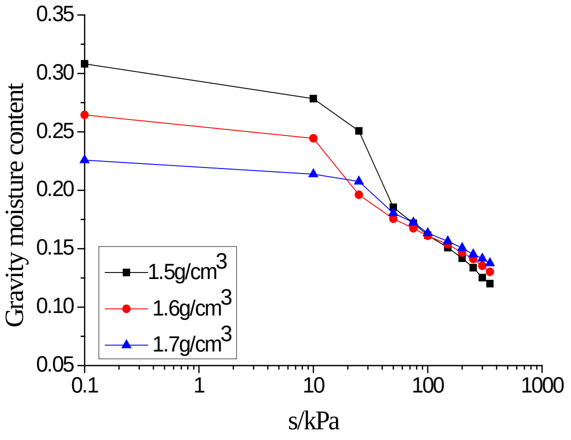
Through comparison between the three SWCCs under different net mean stresses, the initial water contents of the three samples are slightly different due to an error in the process of sample saturation, which is a secondary factor compared with the net mean stress and is negligible. According to further analyses, when the matric suction is less than 25 kPa, the three are slightly different, which might arise from the low matric suction; when the matric suction exceeds 25 kPa, the three become increasingly different, and move to the bottom left with the increase of net mean stress, that is, in the event of same matric suction, the water content decreases with the increase in net mean stress.

Particularly, the demarcation point of 25 kPa is not necessarily the air-entry value of soils, which needs to be obtained through further reduction of the imposed air pressure or fitting with a proper mathematical model of SWCC.

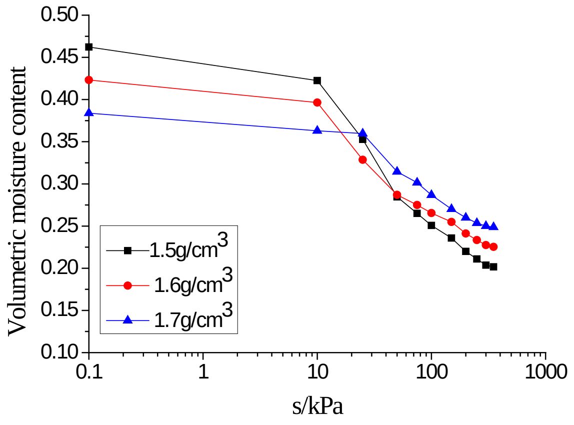
Effect of initial dry density on SWCC

The SWCCs at different initial dry densities are shown in Figure 3.

Through comparison between Figures 3(a) and 3(b), there are some differences between the SWCCs expressed with gravitational water content and volumetric water content in the test points in the upper part and the points of intersection, which arise from the difference in initial dry density and the continuous change in sample volume in the testing process.



(a) Presentation with gravity moisture content



(b) Presentation with volumetric moisture content

Fig. 3. SWCC under different dry density

However, the two figures present roughly the same form, so an analysis is mainly made on the effect of initial dry density on the SWCC expressed with volumetric water content.

According to Figure 3, similar to the SWCCs under different mean stresses, each of the SWCCs at different initial dry densities is divided into 2 different sections based on a demarcation point. When the initial dry density ρ_d=1.5 g/cm^3 and ρ_d=1.6 g/cm^3, the demarcation point s=10 kPa; when ρ_d=1.7g/cm^3, s=25 kPa. In the first section, with the increase in matric suction, the water content slightly changes; in the second section, when the matric suction reaches a certain value (air-entry value of soils), the water content approximately linearly decreases with the increase in matric suction. The mechanism of the interaction between matric suction and water content is the same as that for net mean stress.

According to Figure 3, there are large differences between the SWCCs at different initial dry densities. When the initial dry density ρ_d=1.5 g/cm^3, the initial water content is maximum, followed by that when ρ_d=1.6 g/cm^3; when ρ_d=1.7g/cm^3, the initial water content is minimum. This is because the water contents in saturated samples are different due to the difference in soil compactness and the more compact the soils, the lower becomes the water content. When the matric suction is large, the water content in the soils of the initial dry density ρ_d of 1.7 g/cm^3 is maximum, showing that the soils of high dry density have a strong ability to hold water. From qualitative point of view, although no air-entry value has been measured through the test, we may infer that the value is maximum when ρ_d=1.7g/cm^3 based on the demarcation points and forms of the SWCCs at different initial dry densities. Moreover, following the maximum slope in the second section when ρ_d=1.5 g/cm^3, the slope when ρ_d=1.6g/cm^3 is greater than that when ρ_d=1.7g/cm^3, and the SWCC slope (dehumidification rate) is maximum in the event of low dry density, that is, with the increase in matric suction, the less the dry density, the higher becomes the dehumidification rate (dewatering rate). There are large differences between the samples of same volumetric water content and different dry densities in matric suction.

Accordingly, in relation to remolded loess, dry density has a great effect on SWCC, for the reason that the change in density leads to a change in the pore size of soils and the radius of curvature of the meniscus in soils. With the increase in dry density, the void ratio is reduced, thus leaving it more difficult for air to enter and depart from soils and for water to discharge from soils. Therefore, the air-entry value is large for samples of high dry density. In addition, the dehumidification rate is low when the degree of saturation of the samples of high initial dry density decreases, so the water content in the samples of high initial dry density is high in case of large matric suction。

Results of fitting with Van Genuchten model and its analysis

Through analysis of the results of the SWCC test in the event of different net mean stresses and initial dry densities, it is highly nonlinear. In the process of fitting data with different mathematical models, the authors found that some indicators which could not be obtained through tests may be obtained through fitting of the test results (volumetric water contents under different matric suctions) with the Van Genuchten model, thus comprehensively analyzing the effect of net mean stress and initial dry density on SWCC.

Introduction to Van Genuchten model

Through research on SWCC, in 1980 Van Genuchten *et al.* proposed an expression between volumetric water content and matric suction, which is called Van Genuchten (hereinafter called "VG") model. The model is a mathematical equation in the form of power function. Due to its definite parameters and wide applicability, it is widely used in the fields of geotechnical engineering and soil research [21]. The expression is as follows:

$$\theta=\theta_r+\frac{\theta_s-\theta_r}{\left[1+(\alpha\psi)^n\right]^{(1-m)}} \qquad (3)$$

wherein, θ—volumetric moisture content; θ_r—residual moisture content; θ_s—saturated water content; ψ —the matrix suction of soil; α, m, n—fitting parameters; α relates to the air-entry value and is expressed in kPa^{-1}; m and n relate to the curve form.

Afterwards, Van Genuchten *et al.* found the correlation between m and n (i.e. m=1-1/n). Through simplification of the above equation into equation (4), the VG model becomes more applicable.

$$\theta=\theta_r+\frac{\theta_s-\theta_r}{\left[1+(\alpha\psi)^n\right]^{(1-1/n)}} \qquad （4）$$

Fitting result in the event of different net mean stresses

In combination with RETC, with the user-defined function module of the software of Origin, the VG model is defined to fit the data obtained from the test. To ensure the fitting accuracy, evaluation is made on the fitting effect based on Adj.R^2 (adjust R square).

According to Figure 4, the curve fitted with the VG model approximately conforms to the measured data. In Table 3, Adj.R^2 is over 0.93, showing that the test data may be well fitted and SWCC may be described with the VG model.

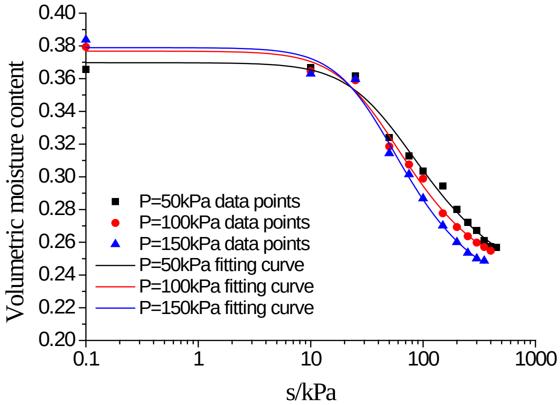


Fig. 4. Fitting curves of samples under different net stress

Table. 3 Fitting parameters of test data under different net stress

Sample status	θ_s	θ_r	α	n	Adj. R^2
P' =50kPa	0.3829	0.2302	0.0272	1.7520	0.9664
P' =100kPa	0.3812	0.2271	0.0321	1.8310	0.9312
P' =150kPa	0.3790	0.2231	0.0283	1.8093	0.9875

SWCC form may be reflected by fitting parameters. According to the fitting parameters in Table 3, with the increase in net mean stress, the residual volumetric water content θ_r gradually decreases but slightly changes, and the fitting parameters α and n slightly change, making it impossible to reflect an obvious rule of change. This might be because net mean stress has no great effect on SWCC and there is a small number of test objects and a certain error in fitting.

Fitting results in the event of different initial dry densities

With the user-defined function module of the Origin software, the test data in the event of different initial dry densities were fitted by the least square method, yielding the result shown in Figure 5. The parameters fitted with the VG model are listed in Table 4.

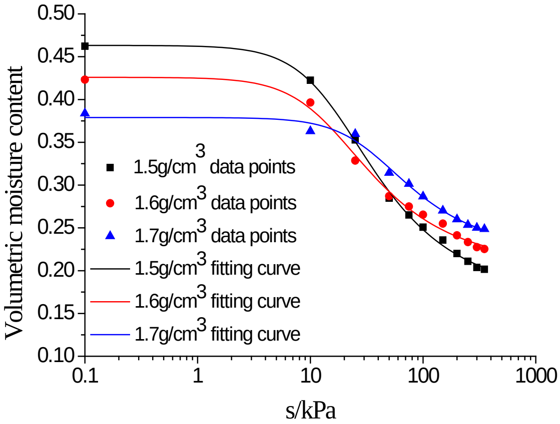


Fig. 5. Fitting curves of samples with different initial dry density

Table. 4 Fitting parameters of test data under different initial dry density

Sample status	θ_s	θ_r	α	n	Adj.R^2
ρ_d=1.5g/cm^3	0.4632	0.1723	0.0632	1.7217	0.9976
ρ_d=1.6g/cm^3	0.4259	0.2057	0.0607	1.7316	0.9924
ρ_d=1.7g/cm^3	0.3790	0.2231	0.0283	1.8093	0.9875

According to Figure 5, in relation to the three curves, the fitting effect is good and the Adj.R^2 is high, being over 0.98.

Different sample states are subject to the fitting parameters and SWCC form. According to Table 4, when the initial dry density is high, the saturated volumetric water content θ_s is low. This is because the pore volume of the samples of high dry density is low and the water content in the samples is accordingly low; the larger the initial dry density, the higher becomes the residual volumetric water content θ_r; with the increase in initial dry density, the fitting parameter α which relates to the air-entry value of soils decreases, but the fitting parameter n which relates to the curve form slightly changes, which is consistent with the result of the research made by Wang *et al.* [22]. Accordingly, the effect of initial dry density on SWCC is mainly subject to the parameters of θ_r (residual volumetric water content) and α (relevant to air-entry value), but slightly depends on n. In other words, the larger the initial dry density, the lower become the pore size and the radius of curvature of the capillary meniscus, making larger pressure become necessary for air to enter soil pores and thus leaving the air-entry value become greater. Similarly, when the matric suction is high and the volumetric water content keeps the same, the higher the initial dry density, the larger becomes the matric suction. Furthermore, the soils of high initial dry density are of low permeability, so the residual volumetric water content is high.

CONCLUSIONS

(1) Measuring matrix suction is important for SWCC research, but most authors have not considered the stress state and volume deformation of samples in the testing process. The proposed FLSY10-1 stress-strain unsaturated soil triaxial apparatus may be used to study the effect of net mean stress on SWCC by considering the change in volume.

(2) From a broad point of view, each of the SWCCs which consider the effect of mean stress and density is divided into 2 sections based on a demarcation point, of which the one that considers net mean stress shows that when the matric suction is low, there is little difference between curves, and when the matric suction exceeds the air-entry value to a definite extent, the water content decreases with the increase in net mean stress. The one that considers density shows that the greater the initial dry density, the lower becomes the dehumidification rate (dewatering rate) and the higher becomes the water content accordingly; through comparison between the SWCCs at different initial dry densities in form and demarcation point, the air-entry value is maximum when ρ_d=1.7 g/cm^3.

(3) Through fitting of the test data with the Van Genuchten model as a 4-parameter equation, based on the evaluation made on the fitting effect with Adj.R^2, we found that this model may be used to fit the SWCC of unsaturated loess in Eastern Gansu. From a broad point of view, the fitting result in relation to the SWCC which considers the effect of net mean stress shows that with the increase in net mean stress, the residual volumetric water content θ_r reduces but slightly changes, and the fitting parameters α and n slightly change; the fitting result in relation to the SWCC which considers the effect of density is mainly subject to the parameters of θ_r (residual volumetric water content) and α (relevant to air-entry value), but slightly depends on n.

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