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Research on Test of Soil-Water Characteristic Curve Model of Unsaturated Loess and Application in Engineering

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Abstract: Soil-water characteristic curve (SWCC) is a very important curve on reflecting mechanics characteristics of unsaturated soil, and plays an important role in researching the hydraulic and mechanical properties of unsaturated soil. To study the soil-water characteristic curve of loess, the value of air-entry suction and residual saturation of undisturbed and remoulded loess were defined based on Van Genuchten model of unsaturated soil, and the tests of soil-water characteristic curve about unsaturated loess were carried out. The variation of soil-water characteristic curve of unsaturated loess and the differences between undisturbed and remoulded loess were analyzed within the control range of suction, and the Van Genuchten model parameters and expressions were received about undisturbed and remoulded loess. The curves of Van Genuchten model about undisturbed and remoulded loess were acquired based on Van Genuchten model expression. At the same time, the results were used to calculate the seepage field of loess slope and the variation of stability before or after rainfall were acquired based on ABAQUS and strength reduction method.

Keywords: *loess; soil-water characteristic curve; model; saturation; suction; slope*

1. Introduction

The curve between suction and water content (weight water content, volumetric water content, saturation, etc.) of unsaturated soil is been called soil-water characteristic curve (SWCC). It is an important feature for unsaturated soil and reflects the relationship between energy and water content, and it is applied in water-soil conservation, slope stability irrigation, weather forecasting, environmental engineering and other aspects (E.C. Leong and H. Rahardjo, 1997). Many mechanical properties of unsaturated soil are closely relativity with the SWCC (D.G. Fredlund, A.Q. Xing, 1996), so research the SWCC has an important significance in the study of unsaturated soil mechanics.

The soil-water characteristic curve model of unsaturated soil is the foundation of researching the SWCC. Many scholars had studied it and a number of mathematical models (S. Nam,et al, 2009; W.S. Sillers, et al, 2001; W.S. Sillers, et al, 2001) about soil-water characteristic curve had been presented after Van Genuchten model (M.T. Van Genuchten,1980) and Fredlund model (D.G. Fredlund,1994) been presented. Shada (2012) presented a new unsaturated soil-water characteristic curve model based on Fredlund model.

The experiment and model are complementary, model is based on statistics and analysis of test data, while the test is a basic method to ascertain model parameters and validate model. A series of experiments had been carried out by the scholars around the world. Khattab (2006) had researched the soil-water characteristic curve of Iraq's expansive soil under high suction, and the results showed that the distribution of SWCC about expansive soil was S-shaped under high suction. Sun De-an (2013), Tan Xiao-hui (2013) researched the SWCC of Hefei expansive soil and Nanyang expansive soil. Wang Dong-lin (2009) had researched the influence of compaction work, compaction moisture content, dry density, stress history and specimen stress state for unsaturated remoulded clay used pressure plate apparatus and GDS unsaturated triaxial apparatus, and fitted the soil-water characteristic curve with the least squares method. Li Ping (2013) measured the soil-water characteristic curve of undisturbed soil with Malan loess by tonometry method, and used three theoretical models to fit the experimental data.

Soil-water characteristic curve about unsaturated soil had been researched by many scholars, but the SWCC about loess need to be further researched. So the SWCC of undisturbed and remoulded loess was researched in this paper, and the result was used to analyze the loess slope.

Model of SWCC about unsaturated soil

The fundamental difference of unsaturated and saturated soil is their compositions. Unsaturated soil is consisted of solid, liquid and gas. The natural state of soil is unsaturated from the results of microscopic scan and the cognition of Fredlund (1993). Some internal pores of unsaturated soil are communicated with the atmosphere, and others are closed pores. At the same time, the body of water in the presence of unsaturated soil have solid water, liquid water and gaseous water, liquid water could been divided into free water and bound water.

Saturated state is an ideal state for soil from the composition of unsaturated soil and it is impossible to acquire a soil that the saturated is equal to 100%. So the intersection point of extension line of SWCC's first phase with suction axis when saturation is equal to 100% is defined as the air-entry suction in this article. Solid water of unsaturated soil is water that present in the mineral particles of soil or water that inside the crystal lattice of minerals structure, and strong binding water is close to the surface of soil particles. There's water always in the soil no matter how much the suction, so the residual saturation is defined in this article when saturation will not vary with increasing of suction saturation.

With the development of this field, a lot of soil-water characteristic curve models used to describe unsaturated soil were proposed and improved, but Van Genuchten model and Fredlund model was been used usually. These two models similar in form, so this article only describes and analyzes the Van Genuchten Model.

Van Genuchten pointed out the relationship of volumetric water content and suction was power function through the research of soil-water characteristic curve about unsaturated soil, and the formula of Van Genuchten model is expressed as:

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

Where θ is volumetric water content, θ_s is saturated water content, θ_r is residual moisture content, s is soil suction, α 、 n and m are test parameters, m usually is considered $1\text{-}1/n$.

The saturated water content and residual moisture are known parameters for a specific soil under certain condition from Van Genuchten model. Therefore, the relative volume water content θ_n is presumed in this paper, and it is expressed as:

$$\theta_n=\frac{\theta-\theta_r}{\theta_s-\theta_r} \tag{2}$$

From the formula of three-phase conversion, the relationship between saturation with quality water content and volumetric water content is expressed as:

$$w=\frac{1}{\rho_d}\theta \tag{3}$$

$$S_r=\frac{d_s}{e\cdot\rho_d}\theta=\frac{d_s}{e}w \tag{4}$$

By Eq.(1) and Eq.(4), the relationship of quality water content, saturation and suction is expressed as:

$$\frac{w-w_r}{w_s-w_r}=\frac{1}{\left[1+(\alpha s)^n\right]^m} \tag{5}$$

$$\frac{S_r-S_{rr}}{S_{rs}-S_{rr}}=\frac{1}{\left[1+(\alpha s)^n\right]^m} \tag{6}$$

Through Eq.(2) and Eq.(6), the relationship of saturation and suction is expressed as:

$$S_r=S_{rr}+\frac{S_{rs}-S_{rr}}{\left[1+(\alpha s)^n\right]^m} \tag{7}$$

$$S_n=\frac{1}{\left[1+(\alpha s)^n\right]^m} \tag{8}$$

Research on the test of SWCC about loess

Test equipment and sample preparation

To measure suction, water content and saturation of unsaturated soil, the instrument of this test is pressure plate apparatus, and the soil-water characteristic curve is acquired after test. The pressure plate apparatus used this test was upgraded by Sun Shu-guo(2006) as Fig.1.

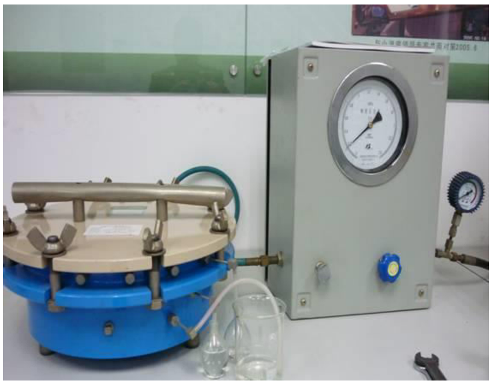


Fig.1 *The instrument of pressure plate*

The object to research the SWCC of unsaturated soil is loess in this paper. The undisturbed soil for test derived from Heping town of Gansu province. The initial physical parameters of the sample are listed in Table 1. The undisturbed soil sample is crafted in laboratory. The initial dry density of the remoulded soil sample is controlled as 1.329g/cm^3. All the samples were saturated by the method of pumping vacuum before test.

Table 1: *Initial physical parameters of loess*

Specific density (g/cm^3)	Water content (%)	Dry density (g/cm^3)	Wet density (g/cm^3)	Saturation ratio(%)
2.71	9.463	1.329	1.4548	24.679

Test program

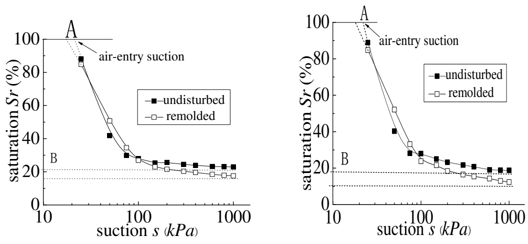
The clay plate must be saturated three times under the pressure is equal to 200kPa before the sample was put into the pressure plate apparatus. After that, take out the saturated sample from the saturated tank and put into the pressure plate apparatus after weighing the initial weight of sample by the electronic balance that it's accuracy is 0.001g. Through the technique of axis translation (2006) the pressure applied in soil is equal to suction when the clay plate is saturated. To obtain water content of soil under different suctions, the pressure is controlled with 11 level loading, respectively 25kPa, 50kPa,75kPa,100kPa, 150kPa, 200kPa, 300kPa, 400kPa, 600kPa, 800kPa, 1000kPa.Use precision electronic balance to weigh the quantity of water that is drainaged after soil drainaging stable at each level loading, and calculate the saturation S_r of soil sample at the same time.

Test results

According to this test plan, the saturations of undisturbed and remoulded loess under different suctions are calculated and listed in Table 2. The SWCC of soil sample is acquired in the plane of $s-S_r$ after the test, and as shown in Fig. 2.

Table 2: *The suction and degree of saturation of loess*

Suction s（kPa）			25	50	75	100	150	200	300	400	600	800	1000
Saturation S（%）	Test 1	Undisturbed	88.16	41.78	29.89	27.97	25.66	25.35	24.49	23.91	23.21	23.04	22.98
		Remoulded	84.79	50.72	34.53	26.93	22.98	21.53	20.31	19.61	18.45	17.87	17.58
	Test 2	Undisturbed	88.85	40.29	28.14	27.97	25.01	23.21	21.71	20.77	19.03	18.86	18.81
		Remoulded	84.71	52.11	33.13	23.79	21.59	18.39	16.48	15.43	14.27	13.01	12.36



(a) Test 1 *(b) Test 2*

Fig.2 *The soil-water characteristic curve of undisturbed and remoulded loess*

Fig.2 is the SWCC of undisturbed and remoulded soil sample from two parallel tests. It shows from this figure that the developing curve of SWCC about undisturbed and remoulded soil sample has two-stage in the range of controlling suction. The first stage is that when suction of soil sample is less than 100kPa, and saturation of soil decreases sharply with increasing of suction in this stage. The suction of intersecting point that SWCC's extension with saturation is equal to 100% is defined air-entry value of soil. The second stage is that when suction of soil sample is 100kPa $\leq s \leq$ 1000kPa, and saturation of soil decreases slowly with increasing of suction in this stage. The SWCC parallels with horizontal axis when suction is continuous increase. The saturation is defined residual saturation when saturation will not vary with increasing of suction from figure and the water content is defined residual water content.

The air-entry suction and residual saturation are acquired of soil sample from Fig.2 and listed in Table 3. Table 3 shows that the air-entry suction of undisturbed and remoulded soil is about 21.99kPa and 17.94kPa and the residual saturation of undisturbed and remoulded soil is about 20.48% and 13.29%.

Table 3 : *The value of air-entry suction and residual saturation of silty clay*

		Air-entry suction（kPa）	Residual saturation（%）
Test 1	Undisturbed	21.63	21.25
	Remoulded	17.54	14.55
Test 2	Undisturbed	22.35	19.71
	Remoulded	18.33	12.04

The air-entry suction of undisturbed soil is higher slightly than remoulded soil from Fig.2 and Table 3. Which maybe relate to the differences of their structures. Overall, when suction range from 20kPa to 100kPa the water content's decreasing trend of undisturbed soil is stronger than that of remoulded soil. When suction range from 100kPa to 1000kPa the suction of undisturbed soil is higher than that of remoulded soil under same water content. When the saturation of undisturbed soil is senior the water of soil will drainage quickly with loading little suction. This maybe undisturbed soil has a lot of pore and connection of pore water is good. But when the saturation of undisturbed soil is low, the pore water will drainage slowly under the interaction of pore water and pore gas. Remoulded soil sample is acquired with compaction, so the pore of remoulded soil sample is very homogeneous and has few big pore. This is why undisturbed and remoulded soil has different SWCC in Fig.2.

The Van Genuchten model of unsaturated undisturbed and remoulded soil sample are acquired through this test and the test parameters as shown in Table 4.

Table 4 : *The Van Genuchten model parameters of loess*

Parameter	α	m	n
Undisturbed	0.041	0.682	3.148
Remoulded	0.029	0.659	2.933

Model curve

The saturation of saturated soil is assumed 100% by soil mechanics, so the parameter S_{rs} of Van Genuchten model is equal to 100%. The residual saturation and test parameters are acquired through this test and the results are substituted into Eq.(7) and Eq.(8), so the equation of Van Genuchten model is expressed as:

$$S_r = 20.48 + \frac{79.52}{\left[1+(0.041s)^{3.148}\right]^{0.682}} \qquad S_n = \frac{1}{\left[1+(0.041s)^{3.148}\right]^{0.682}} \tag{9}$$

$$S_r = 13.29 + \frac{86.71}{\left[1+(0.029s)^{2.933}\right]^{0.659}} \qquad S_n = \frac{1}{\left[1+(0.029s)^{2.933}\right]^{0.659}} \tag{10}$$

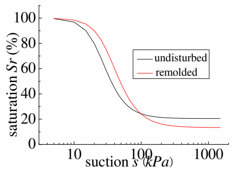


Fig.3 *The curve of Van Genuchten model*

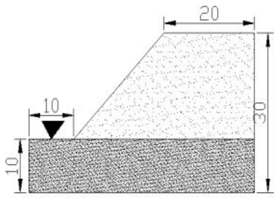


Fig.4 *The model of slope*

The curves of Van Genuchten model about undisturbed and remoulded loess are acquired according to the equation of Van Genuchten and OriginPro, and they are shown in Fig.3.The regularity for change of SWCC can be reflected fully in the curve of model especially when suction is too less or high. Fig.3 shows the shape of SWCC is S-style and it has a little difference with Fig.2. The regularity of SWCC about undisturbed soil is same as remoulded soil, but the amplitude and demarcation point for each stage has slightly different.

The equation and curve of Van Genuchten model can be used to design engineering or analyze seepage flow when engineer has no time or no condition to test.

Application in slope engineering

The major factors of stability for homogeneous soil slope are seepage pressure and seepage field, and seepage field of soil slope usually vary under the condition of rainfall. Soil slope maybe failure when the strength of rainfall is too big or the time of rainfall is too long. The Van Genuchten model acquired according to test is used to research the stability of loess slope in this paper based on ABAQUS.

Slope model and soil parameter

The model of homogeneous loess slope is shown on Fig.4 and the angle of slope is 45°, the height of slope is 20m, water line is located at the foot of slope.

Use ABAQUS to analyze the stability of loess slope includes elastic strain and plastic strain, so the plastic model of soil select Mohr-Coulomb model. And the standard of failure is that calculation does not converge. According to experiment for loess, the mechanical parameters are acquired and listed in Table 5, and the relationship between permeability coefficient and saturation is shown in Fig.5.

Table 5: *Initial parameters of loess slope*

E(MPa)	v	c(kPa)	φ(°)	ρ (g/cm^3)	e	k(m/s)
10	0.3	15	30	1.329	1.2	6.944e-6

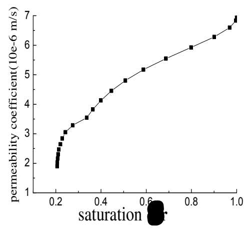


Fig.5 *The curve of permeability coefficient and saturation*

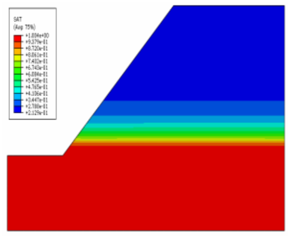


Fig.6 *The saturation of slope before rainfall*

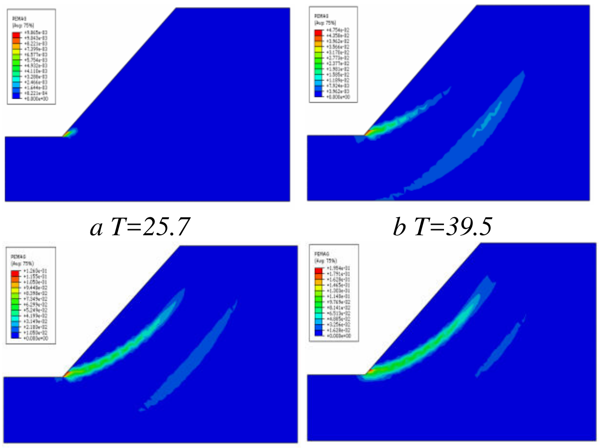
In order to analyze the influence of rainfall for the stability of loess slope, the strength of rainfall is assumed 1e-7mm/h(no rainfall) and 20 mm/h.

Stability of slope before rainfall

The stability of soil slope is researched before rainfall based on ABAQUS and strength reduction method.

Fig.6 is the nephogram of saturation for slope before rainfall. The saturation of slope is very homogeneous from this nephogram, while the saturation of slope is equal to 1 under water line and the saturation of slope homogeneously decreases to 0.2129. The residual saturation of soil slope is same as that in SWCC test.

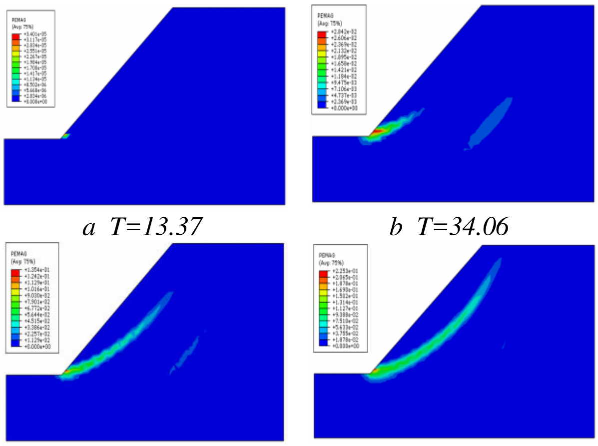
Fig.7 are nephograms of plastic zone for soil slope under different time step when coefficient of strength reduction is equal to 1.470. Plastic strain is yielded in the toe of slope when time step is 25.7 from Fig.7. When time step range from 25.7 to 39.5 main plastic zone of slope develops slowly from the toe and the subordinate plastic zone of slope appears; when time step range from 39.5 to 45.01 main plastic zone of slope develops rapidly and the subordinate plastic zone decreases gradually with the time step growth, so soil is compacted in this stage; when time step range from 45.01 to 46.56 main plastic zone of slope up to the roof of slope and the subordinate plastic zone become very small, and plastic displacement of toe up to 0.195m when slope slide.



a T=25.7 *b T=39.5*

c T=45.01 *d T=46.56*

Fig.7 *The plastic range of slope before rainfall*



a T=13.37 *b T=34.06*

c T=39.53 *d T=40.79*

Fig.10 *The plastic range of slope after rainfall*

Fig.8 shows horizontal displacement of toe point under different strength reduction factors. When strength reduction factor is less than 1, horizontal displacement of toe point is very small and can be supposed no horizontal displacement; when strength reduction factor range from 1 to 1.283, horizontal displacement of toe point increases slowly with increasing of reduction coefficient factor; when strength reduction factor range from 1.283 to1.470, horizontal displacement of toe point increases rapidly with increasing of reduction coefficient factor, and horizontal displacement of toe point up to 0.289m when calculation does not converge. So the factor of safety for slope is supposed 1.470 before rainfall.

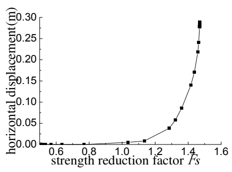


Fig.8 *The horizontal displacement of slope toe before rainfall*

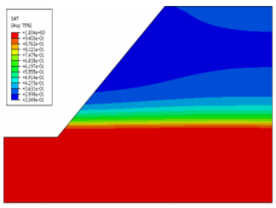


Fig.9 *The saturation of slope after rainfall*

Stability of slope after rainfall

Fig.9 shows the nephogram of saturation for slope after duration of rainfall is equal to 42 hours. The saturation of slope is not homogeneous from this figure, and it is different with Fig.6. There are two phreatic lines in the slope after rainfall, the phreatic line near the roof of slope caused by rainfall and the height of phreatic line caused by ground water gradually rise, so the unsaturated region decreases after rainfall. At the same time, the minimum saturation of slope is 0.2349 because of infiltration caused by rainfall and it is greater than the residual saturation. The saturation of roof also ranges from 0.2129 to 0.299.

Fig.10 are nephograms of plastic zone for soil slope with the infection of rainfall under different time step when strength reduction factor is 1.349. Plastic strain is yielded in the toe of slope when time step is 13.37 from this figure. When time step range from 13.37 to 34.06, main plastic zone of slope develops slowly from the toe and the subordinate plastic zone of slope appears. When time step range from 34.06 to 39.53, main plastic zone of slope develops rapidly and it develops as circular shape, but the rate of development more quickly than in previous stage. At the same time, subordinate plastic zone still exists with the time step growth in this stage. When time step range from 39.53 to 40.79, main plastic zone of slope up to the roof of slope and the subordinate plastic zone disappears, and plastic strain of toe up to 0.225m when slope slide.

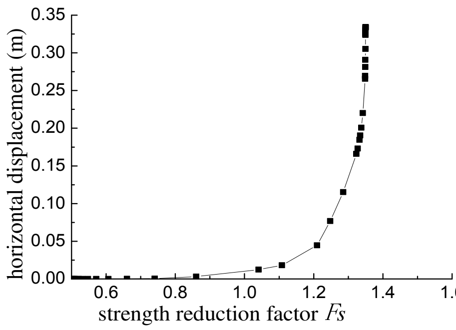


Fig.11 *The horizontal displacement of slope toe after rainfall*

Fig.11 shows horizontal displacement of toe point under different strength reduction factors when the strength of rainfall is equal to 20mm/h. Regularity for change of horizontal displacement with strength reduction factor is similar as no rainfall and distributed three phases. At last, horizontal displacement of toe point up to 0.35m when calculation does not converge. So the factor of safety for slope is supposed 1.42 after duration of rainfall is 42 hours.

Rainfall has a greater effect on development of plastic zone for soil slope from Fig.7 and Fig.10. The plastic zone of slope under rainfall appears earlier than that no rainfall, and the sliding of slope also early after rainfall. At the same time, the factor of safety decreases from 1.470 to 1.349 under the effect of rainfall from horizontal displacement of toe point with strength reduction factor. So the rate of safety factor reduction is 8.23%. Soil slope probably slide after rainfall if the safety factor of slope is about 1.1. The influence of rainfall on the stability of soil slope can be described as"hang on a hair". So it has great significance to escape the sliding of slope and decrease economic loss if consider the influence of rainfall when design or analyze the stability of unsaturated soil slope.

Conclusions

The model and test of soil-water characteristic about unsaturated soil are researched in this paper, and the air-entry suction and residual saturation of loess are obtained through test. The regularity and difference of SWCC about undisturbed and remoulded loess are analyzed, and the results are applied to analyze the stability of loess slope. The main conclusions are as followed:

The mathematical model of saturation and suction about unsaturated soil is obtained basis on Van Genuchten model.

The soil-water characteristic curves for undisturbed and remoulded loess are obtained through the test of pressure plate apparatus, and the differences and reasons of curves are analyzed basis on the results of test.

The air-entry suction and residual saturation of undisturbed and remoulded loess are defined and obtained, the air-entry suction of undisturbed and remoulded soil about 21.99kPa and 17.94kPa, the residual saturation of undisturbed and remoulded soil approximately 20.48% and 13.29%.

The model parameters and model curves of Van Genuchten for undisturbed and remoulded loess are acquired through Van Genuchten model and test results.

The Van Genuchten model of undisturbed loess is used to calculate the infiltration field of soil slope, and the regularity of stability for slope is acquired under rainfall based on ABAQUS and strength reduction method, so the result of this paper can be used to design and analyze soil slope engineering.

Acknowledgments

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