

A method for determining unsaturated strength parameters in stability analysis of loess slope

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Abstract. In recent years, with the rapid development of social economy and progress of human activities in loess area, the Loess Plateau become one of the areas with the most serious soil erosion and the most frequent occurrence of geological disasters in the world. Landslide, collapse, debris flow and ground subsidence are common geological disasters in the Loess Plateau, resulting in a more fragile ecological environment. Therefore, it is very important to accurately predict the stability of loess slope for engineering safety and ecological protection in loess region. But loess is a typical unsaturated soil. the formula of unsaturated strength is seldom used in practical applications. The reason is that the matric suction is difficult to measure. And it cannot be applied in engineering practice. In this paper, based on unsaturated soil shear strength formula of Fredlund, the direct shear test under different moisture content is conducted with the samples of Q1 loess. The effective cohesion and the effective internal friction angle are obtained. Through the matric suction test, the soil-water characteristic curve is plotted. Combined cohesion and matric suction, the strength parameters of unsaturated loess in formula of Fredlund can be informed.

1 Introduction

Unsaturated soil is more widely used in engineering. Up to now, in practical engineering, unsaturated soil is generally regarded as saturated soil to study strength and deformation, but the mechanical properties of unsaturated soil are not considered, resulting in inaccurate research results.

However, in order to the complexity of the engineering characteristics of unsaturated soil and the difficulty of suction measurement^[1], the research on the strength of unsaturated soil cannot be applied in engineering practice. Therefore, the research on the strength theory of unsaturated soil and its application in engineering is undoubtedly the focus and direction in the future^[2,3].

Loess is a typical unsaturated soil distributed in most of China. The sharp decrease of loess strength when exposed to water is the main reason for the geological disasters and project failure, such as landslide and collapse.

Due to identify the strength characteristics of the unsaturated loess, precise parameters must be selected in the strength formula of the unsaturated loess. Then it can accurately predict the stability of the slope of the unsaturated loess, for the construction and safe operation of the project in the loess area.

At present, the widely accepted strength expressions of unsaturated soils are as follows:

$$\tau_f = c' + (\sigma - u_a) \tan \varphi' + (u_a - u_w) \tan \varphi^b \quad (1)$$

There, τ_f is the shear strength of the failure surface; c' is the effective cohesion (the shear strength when the normal effective stress is zero); $(\sigma - u_a)$ is the normal effective stress on the failure surface; φ' is effective internal friction angle; $(u_a - u_w)$ is the matric suction; φ^b is friction Angle corresponding to matric suction.

This shear strength formula of unsaturated soil is proposed by Fredlund^[2]. In this formula $\tan \varphi^b$ refers to the rate at which the shear strength increases with the increase of suction $(u_a - u_w)$. The first two items can be obtained from the conventional test of saturated soil, while the third item can only be determined by the relevant test of unsaturated soil. The normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ are regarded as two independent variables in the expression of the mechanical properties of unsaturated soils. The effect of suction on strength is considered separately rather than simply as an increase in effective stress.

Therefore, it is beneficial to understand and analyze the strength composition of unsaturated soil, especially the term $(u_a - u_w) \tan \varphi^b$ of the equation can be intuitively understood as a component of the false cohesion of unsaturated soil.

Based on Fredlund's formula of shear strength of unsaturated soil, laboratory tests of unsaturated loess were carried out. First, consolidated slow shear tests were carried out, and the effective stress indexes c' and φ' were obtained. Secondly, the relationship between soil suction and water content was tested and the soil-water characteristic curve was obtained. Then, the linear relationship between shear strength and suction is

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obtained. At last, the parameters in the strength formula can be determined through the calculation and analysis.

2 Methodology

2.1 Test materials

The soil sample is taken from Q₁ loess at the bottom of the Yan'lian landslide. The landslide occurred on October 21, 2010. The landslide destroyed 24 oil pipelines at the foot of the slope, interrupted the road on the slope, and suspended 33 original oil tanks at the back edge, causing huge economic losses. However, the landslide slipped intermittently for two days without casualties^[4].

In order to determine the specific physical and mechanical properties of the loess used in the test, the basic physical parameters of the loess used in the test were obtained through conventional geotechnical tests, as shown in Table 1. Among them, the density was cutting ring method, the moisture content was drying method (105°C), the specific gravity was specific gravity bottle method, the plastic limit was rolling method, and the liquid limit was taper loss method (76g). The particle size distribution was measured by BetterSize2000 laser particle size analyzer, and the grain size distribution curve of the soil sample was shown in Figure 1.

Table 1. the basic physical properties

moisture content	w	%	19.9
density	ρ	g/cm^3	1.890
dry density	ρ_d	g/cm^3	1.610
specific gravity	Gs		2.71
void ratio	e_0		0.700
liquid limit	w_L	%	33.7
plastic limit	w_P	%	20.8
plasticity index	I_P		12.90
liquidity index	I_L		-0.07

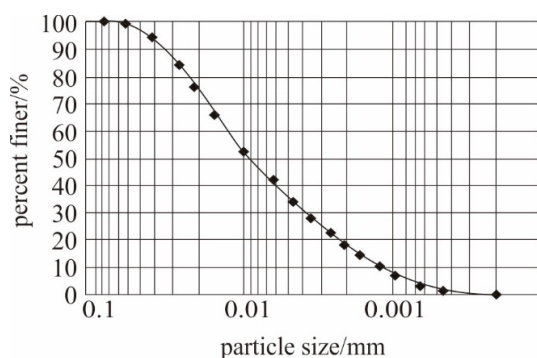


Figure 1. Grain size distribution curve

As can be seen from the figure, clay particles with particle size less than 0.005mm account for 26.4%, silt particles with particle size between 0.005 and 0.075mm account for 71.8%, and sand particles with particle size greater than 0.075mm account for 1.8%. It can be seen that the loess is mainly composed of silty grains and is named as silty clay according to its plasticity index.

Since the sliding surface of this part is nearly horizontal, the loess is shearing out along the bedrock surface, which is equivalent to the stress condition of direct shearing. Therefore, direct shear test is conducted for this group of samples.

2.2 The direct shear test

The shear strength of the samples with different water content was tested by direct consolidation slow shear.

Before the direct shear test, the undisturbed loess was dried and 7 groups of undisturbed soil samples with mass moisture content of 0%, 5%, 10%, 15%, 20%, 25% and 30% were prepared. After that, the undisturbed soil samples with different moisture content were subjected to different normal stresses (50kPa, 100kPa, 200kPa, 300kPa, 400kPa) Consolidating slow shear test was carried out at 500 kPa 600 kPa. The shear rate was set at 0.02mm/min

Titrimetric method is used to configure undisturbed soil samples with different mass water content. The specific operation steps are as follows: according to the natural water content and expected water content of loess, calculate the volume of water to be added, use a dropper to add water to the sample according to the controlled water content, and then wrap the sample with plastic film, put it in the humidifier, stand for a week, until the water is evenly scattered into the sample. The advantages of this method are convenient operation and accurate control of water content, but the disadvantage is that water is not easy to diffuse evenly. As can be seen from the shear surface of the soil sample after the direct shear test, water is basically evenly dispersed in the soil sample, as shown in Fig.2.

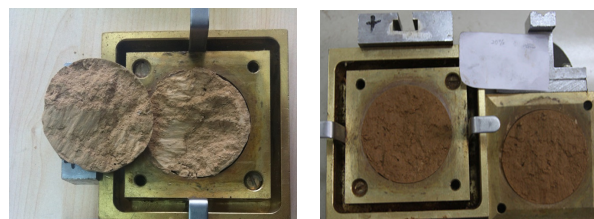


Figure 2. Shear surface of soil sample

2.3 SWCC test

Related parameters in Bishop and Fredlund's unsaturated strength formula need to be determined by combining conventional triaxial tests with soil and water characteristic curves^[5]. Although the axial translation technique is the most accepted method for measuring matric suction at present, it is impossible to prove whether the test environment will affect the soil properties and test parameters. Tension meter is under

the environment of atmospheric pressure measuring, testing environment in accordance with the natural environment, there will be no axis translation method to change the natural environment of soil, although the range is small, but engineering damage occurred in high water cut and low matrix suction state, from engineering sense is desirable, so this method is suitable for engineering measurement of soil^[6,7].

The suction of soil samples in this test is measured by TEN tensiometer. Ten Tension Meter can measure suction in the range of 0~100kPa. Applicable temperature is -20°C~+80°C. The specific operation steps are as follows: take a large soil sample at the sampling point, add water to the sample by stages, change the moisture content of the sample, and take a small amount of soil sample to measure its moisture content. The matric suction was measured with a TEN tensiometer for each stage of water content. First, make a hole about 8cm deep in the center of the square (side length of about 30cm) soil sample, which is basically the same as the diameter of the tension meter. Then, air the ceramic head of the tension meter, inject water into the tension meter, and insert it into the hole vertically. Fill the space between the tension meter and the hole with fine sand with the same moisture content as the soil sample. The test ends when the tension meter reading difference is less than 0.5kPa. The reading on the tension meter is the matric suction of the soil sample at this level of moisture content.



Figure 3. The SWCC test with TEN tension meter

3 Result and discussion

3.1. Experimental results

The results of seven groups of consolidation slow shear tests with different water content are shown in Fig. 4. For each group of normal stress shear curves with different water content, the shear stress at the displacement of 6mm and the corresponding normal stress value are taken to draw the strength curve.

The results of soil-water characteristic curve and the fitting curve are shown in the Fig.5.

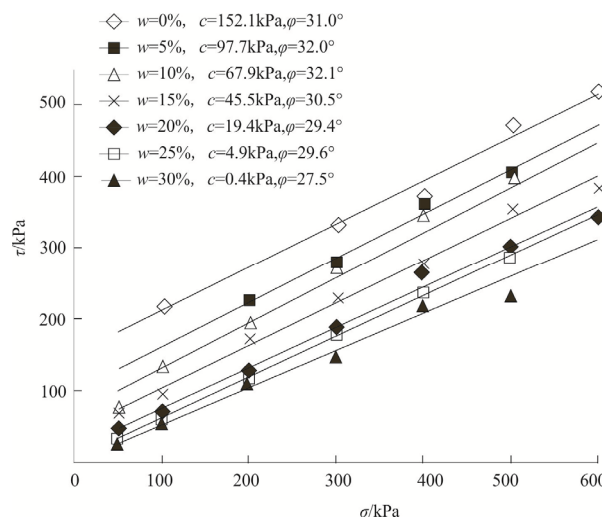


Figure 4. The result of direct shear test

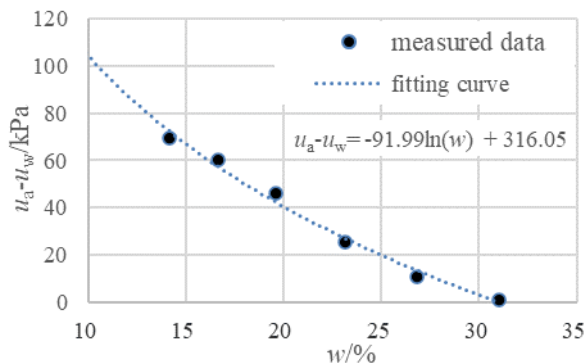


Figure 5. Soil-water characteristic curve

3.2 Unsaturated loess strength parameters

Equations (1) is composed of three parts, the first part is the effective cohesion, the second part is the effective friction, and The third part is the friction caused by matric suction. If the sample is near saturation, the matric suction is 0, which means that the third part of this formula is 0. In this case, the shear strength and internal friction Angle of the sample are the effective shear strength and effective internal friction Angle of the sample. When the moisture content of the sample changes, that is, in the unsaturated state, the third part of the formula is the function of the matric suction, that is, the function of the moisture content.

It is found that the internal friction Angle measured under different water content is approximately constant and the cohesion is always the one value that changes obviously with water content. Therefore, the third term in the formula is regarded as the quasi-cohesive force.

$$c = c' + (u_a - u_w) \tan \phi^b \quad (2)$$

The test measures cohesion at different water content. The soil sample at 30% water content is taken as saturated sample, that is, the cohesion measured at 30% water content is effective cohesion. That is c'=0.4kPa.

With the decrease of water content, the cohesion obtained in the experiment includes the increase of $(u_a - u_w)\tan\phi^b$.

This is partly caused by matric suction, which increases with decreasing water content

Therefore, according to the fitting curve of the matric suction, the relationship between suction and water content is obtained.

The matric suction with water content of 5%, 10%, 15%, 20%, 25% and 30% was obtained by calculation. Based on the analysis of the data and results of direct shear test and matric suction under the above conditions, the relationship between cohesion and matric suction can be obtained as shown in Table 2

Table 2. Relationship between cohesion and matric suction at different water content

moisture content w/ (%)	5%	10%	15%	20%	25%	30%
c/kPa	97.7	67.9	45.5	19.4	4.9	0.4
$u_a - u_w$ /kPa	168.0	104.2	66.9	40.5	19.9	3.2

The data in Table 2 were plotted into a graph of the relationship between cohesion and matric suction, as shown in Figure 6. It is found that there is a good linear relationship between cohesion and matric suction.

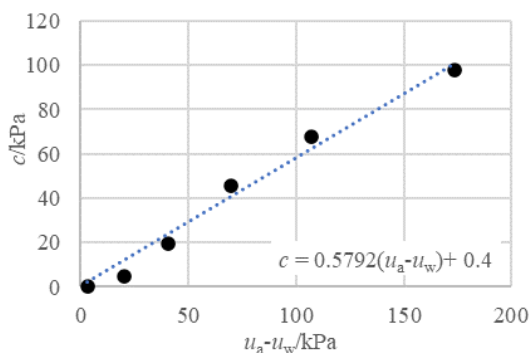


Figure 6. The relationship between cohesion and matric suction

It can be seen from Fig. 6 that there is a linear relationship between cohesion and suction. The suction range is 3.2-168.0kPa, and ϕ^b is a certain value within a limited suction range. Based on the relationship between the matric suction and cohesion, it can be seen the $\tan\phi^b = 0.5792$, that is the $\phi^b = 30.08^\circ$. According to direct shear tests, the effective internal friction Angle is about 30.03° . It is consistent with previous research results^[8]. In fact, the suction friction Angle ϕ^b comprehensively reflects the interaction between water and soil in unsaturated soil, and the study of its value has a great influence on the study of shear strength.

Therefore, the Fredlund unsaturated loess strength parameters ϕ^b can be obtained by direct shear test results and matric suction test.

4 Conclusions

The strength of unsaturated soil consists of four parts: effective cohesion, intergranular friction, matric suction

and solute suction. In general, the concentration of ions in the pore water solution of unsaturated soil is very small, so solute suction can often be ignored. Therefore, the study of strength characteristics of unsaturated soil mainly focuses on the contribution of matric suction to strength.

Based on Fredlund unsaturated soil shear strength formula for theoretical basis, the Yan'lian shaanxi province loess slope as the research object, first through the direct shear test samples under different moisture content moisture content and the relationship between the cohesive force, again through the matrix suction test, draw the soil - water characteristic curve, it is concluded that the moisture content and the relationship between suction and analyze the data, The strength parameter value of unsaturated loess is obtained, that is, the influence of matric suction on the strength of unsaturated loess.

In this test, the method can be directly measured by conventional direct shear tests with different water content. The strength formula based on suction stress avoids the cumbersome measurement of matric suction and is easy to be popularized in engineering practice.

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