Experimental Study on Shear Strength of Unsaturated Loess Based on Different Water Content in Xining Area

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Abstract. Today, the study of shear strength of unsaturated soils has become a hot topic in unsaturated soil mechanics research. There are any number of factors affecting the strength of unsaturated soils. Among these factors, the moisture content has the most significant effect on the shear strength. In this paper, unsaturated loess in Xining is taken as the research object, the triaxial test without consolidation and undrain is used to determine the shear strength and its parameters under the condition of different water content, then the relationship between unsaturated loess’ water content and shear strength parameters is explored, and curve fitting is performed. The relevantly approximate mathematics formulas are obtained. The study can provide strength parameter for slope stability and foundation pit support in Xining.

1. Introduction
With the rapid development of economic construction in the western region of China, the investment of large-scale infrastructure is increasing, and high-rise buildings and high-speed railroads are rapidly developed. However, these projects are mostly based on unsaturated loess with strong collapsibility, large void ratio, and strong structural properties. Because the foundation or roadbed soil of these projects is in the collapsible loess area for a long period of time, it is often because of the collapsibility of loess. As a result, uneven settlement of the project results in seriously negative social impact. The reason for this collapsibility is that when the soil meets water, the moisture content of the soil changes, which in turn causes the suction in the soil to change, and the shear strength of the soil also changes, eventually lead to the destruction of the soil. Therefore, the shear strength test of unsaturated loess in Xining region was studied, and the relationship between the shear strength values of different moisture contents and their parameters was explored, which has guidance function to practical engineering construction.

2. Shear Strength Theory of Unsaturated Soil
Unsaturated soils are more complex than saturated soils. First, the surface tension of the water-gas interface have the water and gas in the pores have different pressures, and the pore water pressure is often negative; second, the simultaneous appearance of the pore gas pressure and negative pore water pressure make the effective stress of the soil no longer equal to the pressure between particles, so that the feasibility of the effective stress principle of saturated soil in unsaturated soil mechanics needs to be re-evaluated. Therefore, the strength formula of unsaturated soil cannot be simply generalized from saturated soil, and its unique strength formula must be established.

At present, the mathematical model for predicting the shear strength of soil unsaturated soil includes the unsaturated shear strength formula expressed by Bishop[1] based on the effective stress...
principle of the single stress variable. The problem of the Bishop formula is the effective stress parameter. Affected by soil structure, stress path and saturation, it is difficult to accurately determine; in addition, Fredlund and other scholars believe that thorium is a soil parameter, and stress state variables should not contain soil parameters. Fredlund proposed the unsaturated shear strength formula (a) based on the expression of double independent stress state variables, which is the normal stress, the matrix suction, the effective cohesion of the saturated soil, the effective internal friction angle of the saturated soil, and the shear resistance. The slope of the intensity as the suction increases. Determining the direct shear or triaxial test required to control the suction force has limited the popularization of Fredlund's formula in engineering applications because of the expensive equipment, complicated testing, and high measurement accuracy requirements.

The Fredlund-Xing [2] model (b) can fit the SWCC test results well, and provide important data for predicting the shear strength of unsaturated soils. The D.G Fredlund [3,4] model (c) relates the contribution of suction to the shear strength and SWCC, and proposes to use SWCC and saturated shear strength parameters ($c$, $\phi$) to predict the unsaturated shear strength to solve the Fredlund unsaturated resistance. Shear strength formula inconvenient application of engineering.

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi_b$$  
(a)

$$\theta_w = \left[ \ln \left( \exp(1) + \frac{\theta}{\phi} \right) \right]$$  
(b)

$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \left[ (\tan \phi') \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right]$$  
(c)

In summary, the theory of shear strength of unsaturated soils is based on the variation of its strength. However, the specific relationship between moisture content and shear strength is not clearly indicated. Therefore, this paper uses conventional triaxial tests to explore the relationship between water content and shear strength parameters of unsaturated loess in Xining area, and to provide data support for studying shear strength theory of unsaturated loess.

3. Test Results and Analysis

3.1 Test results
The shear strength test of loess under different water content was measured by the three-axis unconsolidated undrained shear test in the room as shown in Table 1.

| w /% | c /kPa | $\phi$° |
|------|--------|---------|
| 10   | 37.83  | 25.85   |
| 11.6 | 34.49  | 25.63   |
| 13.9 | 25.80  | 25.25   |
| 15.8 | 18.72  | 24.99   |
| 17.6 | 12.19  | 23.72   |
| 20.8 | 7.5    | 23.59   |

3.2 Data Analysis

3.2.1. Analysis of the relationship between moisture content and cohesion.
The data in Table 1 was numerically simulated with Origin8.5. The result of the fitting was shown in Figure 1.

As can be seen from figure 1, the cohesion of loess decreases with the increase of moisture content in the study. the cohesion decreased rapidly, when the moisture content is less than 17%, the cohesion
decreased slowly when it is greater than 17%. After the regression prediction analysis of the cohesion and moisture content, the relationship between the cohesion (Y) and the water content (x) is:

\[ Y = A \times e^{(-x/B)} + C; \quad R^2 = 0.97766. \]

Among them A=124.93556, B=17.2, and C=-30.8 are test parameters.

![Figure 1. The exponential relationship between water content and cohesive force.](image)

3.2.2. **Relationship between Moisture Content and Friction Angle.**

As can be seen from Figure 2, with the increase of moisture content, the cohesive force is decreasing, presenting a nonlinear relationship. However, there is not much difference, indicating that the water content has little effect on the friction angle.

![Figure 2. The relation curve between water content and internal friction angle.](image)

3.2.3. **Effect of Moisture Content on Shear Strength.**

Because the soil pores contain gas, the shear strength of soil samples contains the contribution of suction. From Figure 3, it can be seen that as the moisture content increases, the strength gradually decreases.
4. Summary
(1) Within the scope of the study, with the increase of water content, the cohesion of soil is continuously decreasing. Through data fitting, it is found that there is an exponential relationship between moisture content and cohesion, which can be approximated by a mathematical formula.

(2) The effect of water content on the friction angle is as follows: With the increase of water content, the friction angle decreases, but the decrease is not significant.

(3) Since the pores of soil samples contain gas, the shear strength of soil samples contains the contribution of suction to it. In soil samples with increasing water content, the shear strength of the soil decreases significantly.

(4) This study can provide strength parameters for the theoretical study of shear strength under the influence of suction.

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