Analysis of deformation and failure characteristics of undisturbed loess under three axis test

LEI Guangyu1,2,3,4, XIE Xiao1,2,3,4

1Shaanxi land engineering construction group
2Key Laboratory of Degraded and Unused Land Consolidation Engineering, the Ministry of Natural Resources
3Shaanxi Provincial Land Consolidation Engineering Technology Research Center
4Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co., Ltd Xi’an 710075

Abstract: The water content has a very obvious influence on the deformation and strength characteristics of loess, which is related to the safety of geological environment. In this paper, the triaxial test of loess is carried out, and the deformation characteristics of the loess are studied. The strength characteristics of different loci are studied. The study shows that as the water content increases, the effective cohesion of loess decreases and the effective internal friction angle changes. The amplitude is not large, indicating that the water content only affects the effective cohesion of the loess and does not affect the effective internal friction angle. When the water content reaches a certain value, the effective cohesion is no longer reduced and remains stable. The corresponding moisture content corresponds to the plastic limit. The Mohr-Coulomb strength theory is suitable for fitting shear failure and bulging deformation. While Griffith The strength theory is more suitable for fitting the splitting failure, indicating that the strength theory suitable for different failure modes is different.

1. Introduction
As a typical unsaturated soil, loess deformation and failure characteristics are not only related to its stress state, but also related to its water-containing state. Therefore, it is necessary to study the deformation and failure mechanism from these two factors. At present, the research on the mechanical properties of loess, especially the deformation characteristics and strength characteristics, has achieved fruitful research results[1-5].

The basic method for studying the deformation and destruction of loess is sampling for indoor testing. The basic principle of testing is that the test conditions and field conditions are as close as possible. Generally, soil damage is only caused by damage and shearing. It is generally considered that the soil is not tensile. As long as there is a tensile stress environment, it is considered to be about to be destroyed. The tensile failure is caused by the collapse or the trailing edge of the landslide. The common landslides are mostly caused by the shear failure of the soil. Generally, the shear strength of the soil can be obtained indoors through the direct shear test and the triaxial test. Since the sliding surface is fixed in the direct shear test, such tests generally represent the case where the sliding surface has been determined. For example, the shear strength of the old landslide is generally a direct shear test. The sliding surface of the old landslide has destroyed the original structure of the loess. After large displacement shearing, it is fully disturbed. After the landslide occurs, it is consolidated for a
long time, so the consolidation shear test of remolded soil can be used. Most of the old sliding surfaces are relatively water-tight, mostly saturated, so the solidified undrained test (fast speed) or consolidated drainage test (slow speed) of saturated remolded soil should be used\cite{6-8}.

2. Test conditions

The samples were taken from the high slope near Nanniwan, Yan'an City. The cylindrical samples of the triaxial test and the ring samples of the conventional test were made on site. The basic physical and mechanical properties of the samples were measured by the test. As shown in Table 1.

| Sampling location | Stratigraphic age | Clay content (%) | Specific gravity (g/cm³) | Bulk density (g/cm³) | Water content (%) | Plastic limit (%) | Liquid limit (%) | Plasticity index | Liquidity index | Dry density (g/cm³) | Void ratio |
|-------------------|-------------------|------------------|--------------------------|----------------------|------------------|------------------|------------------|------------------|----------------|----------------------|-----------|
| Nanniwan          | Q2-2 L5           | 27.4             | 2.71                     | 1.53                 | 13.9             | 37.0             | 22.8             | 14.2             | -0.63          | 1.37                 | 0.972     |

The method of water distribution of the sample is titrated, and the specific steps are as follows:

1. The original sample cut from the field was dried and then measure the dry soil weight;
2. The wet soil was calculated weight corresponding to the corresponding water content based on the dry soil weight and the target moisture content. The calculation formula is as follows:
   \[ m_1 = (1 + 0.01w) \times m_0 \]  
   In the formula: \( m_1 \) - wet soil weight (g); \( m_0 \) - dry soil weight (g); \( w \) - target moisture content (%).
3. The soil sample was dripped from different positions with a dropper. The soil sample was scaled to the wet soil by an electronic balance;
4. The prepared soil sample was wrapped with a rubber film. The both ends were sealed. It was placed in the moisturizer for one week to make the water uniform;
5. The soil sample was removed for triaxial test.

6 kinds of target moisture content were used for water distribution, as shown in Table 2. Among them, the sixth group is a saturated sample. Test the weight of the soil sample before and after the test, and then dry the sample after the test. The dry soil weight and the water content before and after the test were measured. The results are shown in Table 2. Since the target water content of the soil sample is difficult to accurately control, there is some deviation between the measured water content and the target water content. The test uses a consolidated undrained shear test. Due to the loss of water during the consolidation process, the water content after the test is generally lower than before the test.

| Target moisture content \( w_0 \% \) | 1  | 2  | 3  | 4  | 5  | 6  |
|--------------------------------------|----|----|----|----|----|----|
| Moisture content before test \( w_1 \% \) | 6.0 | 11.0 | 16.0 | 21.0 | 26.0 | 30.0 |
| Moisture content after test \( w_2 \% \) | 6.3 | 11.2 | 17.0 | 21.5 | 27.8 | 30.8 |

3. Analysis of failure characteristics of specimens under triaxial test

During the test, five kinds of confining pressures were applied to the soil samples, which were 100 kPa, 200 kPa, 300 kPa, 400 kPa, and 500 kPa, respectively. To observe the deformation and failure characteristics, all samples were photographed and tracked before, during and after the test.
As shown in Fig. 1, by comparing the test curve with the failure mode of the sample, the loess has three failure modes in the triaxial stress environment. That is, splitting damage, shear failure and bulging damage. It is found from the figure that when the confining pressure is lower than 200 kPa and the water content is low, the soil sample undergoes splitting failure, and the fracture surface and the direction of the maximum principal stress are the same. The stress-strain curve shows a typical strain-softening type, and the stress-strain curve peaks. Later, there is a significant stress drop; shear failure occurs in the case of medium confining pressure and medium water content. With obvious shear plane, shear plane and maximum principal stress oblique, stress-strain curve is strain softening. The bulging damage occurs in the case of high confining pressure and high water content. It is a typical plastic deformation. The outer drum of the specimen is axially shortened, and there is no obvious shear plane. The stress-strain curve exhibits strain softening, ideal plasticity and strain hardening. As shown in Figure 1.

Take the water content as the abscissa and the confining pressure as the ordinate. The failure mode of all the soil samples is listed in the coordinates. As can be seen from Fig. 2, the region with low confining pressure and low water content in the lower left corner is splitting. Destruction, shear failure occurs in the upper right part of the cleavage failure zone. That is, the area with high confining pressure and water content; most of the area in the upper right corner belongs to the bulging failure. The area is high water content and high confining pressure. In general, the large area of bulging is the main form of damage, and the series of tests can determine the confining pressure and water content limits for different failure modes.

The strength theory applicable to different failure modes is different. The Mohr-Coulomb strength theory is only suitable for shear failure. The bulging damage is plastic deformation from the macroscopic view and microscopically along the slip line. Movement, so both shear failure and bulging deformation can be fitted by the Mohr-Coulomb strength theory, while the splitting failure can be fitted using the Griffith strength theory.

![Fig.1 Three typical failure modes of Loess](image1)

![Fig.2 Failure modes of loess under different water content and confining pressure](image2)
Different deformation and failure characteristics exist in different positions on the same slope. The loess, which is on the top of the slope, has a small water content, a small confining pressure, and a splitting failure. As mentioned above, when the landslide occurs, the strength of the soil at the top of the slope is sharply reduced and the strength is reduced. It can be ignored. The loess at the bottom of the slope, because the lower part is red clay or bedrock, is a relatively impervious layer, so the confining pressure and water content of the lower soil are very large, and creep damage occurs. In the case of landslide as the strain increases, its shear strength remains stable or increases. It can resist further decline of the slope. In the middle soil, the confining pressure and water content are medium, shear failure occurs, and there is obvious damage surface. After the landslide occurs, the soil still has a certain residual strength.

4. Strength characteristics of the specimen under triaxial test

![Fig.3 Relationship between moisture content and effective cohesion of Loess](image)

| Sample No. | Target moisture content (%) | $c'_q$ (kPa) | $\varphi'_q$ (°) | $c'$ (kPa) | $\varphi'$ (°) |
|------------|-----------------------------|--------------|-----------------|-----------|--------------|
| Y₁         | 6                           | 68.5         | 23.3            | 74.6      | 25.5         |
| Y₂         | 11                          | 25.4         | 22.7            | 27.5      | 24.8         |
| Y₃         | 16                          | 15.4         | 22.9            | 16.7      | 25.0         |
| Y₄         | 21                          | 6.3          | 22.8            | 6.8       | 24.9         |
| Y₅         | 26                          | 3.5          | 22.5            | 3.8       | 24.5         |
| Y₆         | 30                          | 3.2          | 23.1            | 3.5       | 25.2         |

It can be seen from Table 3 that the effective cohesion of the same loess decreases with increasing water content, while the effective internal friction angle is independent of the water content. The friction angles at different water contents are not much different. The relationship between water content and cohesion is shown in Figure 3.

5. Conclusion
In this paper, the strength characteristics of loess under different water contents were studied through triaxial tests on the loess, starting from its deformation and failure forms. It was found that:

1) The effective cohesive force of the same loess decreases with the increase of water content. Effective internal friction Angle is independent of water content. The difference of friction Angle under different water content is very small. When the water content is higher than 21%, the cohesion no longer decreases and remains stable, which is equivalent to the plastic limit value.
(2) The strength theory applicable to different failure modes is different. Both shear failure and bulging deformation can be fitted by the Mohr-Coulomb strength theory, and the fracture failure can be fitted by the Griffith strength theory.

Acknowledgement
The study is supported by Shaanxi Provincial Land Engineering Construction Group Research Project (DJNY2019-22).

References:
[1] Wang Jiading, Zhang Zhouyuan. A Mechanism in Loess Self-load Collapse[J]. Scientia Geographica Sinica, 1999, 19(3): 271-276.
[2] Wang Changming, Ma Donghe, Lin Rong et al. Shear Strength and Constitutive Characteristics of Loess in West Liaoning[J]. Journal of Jilin University(Earth Science Edition), 2010, 40(5): 1105-1109.
[3] Dai Fuchu, Chen Shouyi, Li Chaofen. Analysis of landslide initiative mechanism based on stress-strain behavior of soil[J]. Chinese Journal of Geotechnical Engineering, 2000, 22(1): 127-130.
[4] Pang Xueqing, Hu Zaiqiang, Liu Yin. Experimental study on mechanics properties damage to the loess under the freeze-thaw cycle[J]. Journal of Railway Science and Engineering, 2016, 13(4): 669-674.
[5] GB/T 50123-1999. Geotechnical test method standard[S]. peking: China Planning Press, 1999.
[6] J K Mitchell. Fundamentals of soil behavior[M]. NewYork:John Wiley Sons, 1986.
[7] Wang Yongjia. Discrete element method and its application in geotechnical mechanics[M]. Shenyang: Northeastern University Press, 1991.
[8] Long Jianhui, Li Tonglu, Lei Xiaofeng al. Study on physical properties of soil in sliding zone of loess landslip[J]. Chinese Journal of Geotechnical Engineering, 2007, 29(2): 289-293.