Experimental Study on Stress Paths of Unsaturated Soils

Guangli Sun*, Yining Zhang and Siyuan Yin
Jilin Jianzhu University, Jilin, Changchun, 130118

*Corresponding author e-mail: Z123456zhangyining@163.com

Abstract. The distribution of loess in China is concentrated in the Midwest, which is a typical structural soil. Its structure is extremely special, and its sensitivity to water is also unique. The strength and deformation characteristics of this kind of unsaturated soil have a great influence on the stress it bears. This study starts with the same stress ratio loading of loess with different moisture content and corresponding remolded loess, aiming at the changes of the structure of unsaturated soil under different stress ratios. Based on the comprehensive analysis of structural potential parameters of unsaturated soil under the condition of poor stress, the appropriate hardening parameters are constructed, and the corresponding elastic-plastic constitutive model is established. At first, the corresponding test scheme is designed, and then the test results are analyzed. Finally, the specific analysis is carried out from the constitutive model of stress elastic-plasticity of unsaturated soils.

Keywords: Unsaturated soil, Structural characteristics, Stress path, Constitutive model, Stress ratio

Introduction
Loess has a unique nature, so it needs special attention when carrying out engineering construction on this kind of soil. From the engineering construction, the strength and stability of this kind of unsaturated soil reflects many problems, which is worthy of further study. Specifically speaking, the realistic manifestations include leakage or deformation of irrigation channels, the cracking or collapse of unsaturated soil tunnels and the settlement of highway foundation. Therefore, it is of practical significance to study the stress of unsaturated soil and build the constitutive model of stress elastic-plasticity of unsaturated soils for further analysis.
1. Test plan for this study
The sample used in this study is from Yanglingyuan of Shaanxi Province. It is a loess with developed pores. Its structure is relatively loose and the depth of soil sampling is about 3.2m. It contains a certain amount of calcium core with high compressibility and self weight collapsibility. Table 1 below shows the specific physical indicators of the loess sampled. In addition, the particle composition of loess is mainly 0.05-0.005mm, accounting for 62%. If the particle of loess is more than 0.05mm, it accounts for 7%; and if it is less than 0.005mm, it accounts for 31%.[1]

| Dry density (g/cm³) | Liquid limit (%) | Plastic limit (%) | Plasticity index | Void ratio |
|---------------------|------------------|-------------------|------------------|------------|
| 1.23                | 30.8             | 18.7              | 11.7             | 1.16       |

According to the requirements of the test, the air-dried loess is ground and sieved to remove large particles and other impurities, and the pore size is 0.5mm. Then, the remodeling of the original loess is carried out by the lamination method. The screening conditions are 4%, 9%, 12%, and 17.5% of the initial water content, and finally the full saturation state is explored. The height is controlled at 80 mm, the diameter is set at 39.1 mm, and the difference of prepared dry density is controlled at 0.2 g / cm³ or less. Air-drying method and water film transfer method are used to adjust and control the water content. In the experiment, attention should be paid to the same group to control a single variable. The stress-selection triaxial apparatus for the stress of this test is implemented, and the iso-stress ratio test is performed on the original samples with different initial water contents, as well as the saturated samples and remodeled samples. The stress ratio K is kept constant during the test, and tests are performed at 0.25, 0.5, 0.75, and 1. Different initial water content and different stress ratio can show the characteristics of unsaturated loess structure.[2-4]

2. Analysis of test results of this study
(1) The iso-stress ratio is controlled to study the stress and strain of unsaturated loess.

The data obtained from the specific research are shown in Figure 1, and the stress-strain curves of undisturbed loess and remolded loess show obvious results under different stress conditions. Among them, (a) w = 4%, (b) w = 9%, (c) w = 12%, (d) 2 = 17.5%.

From the four diagrams in Figure 1, we can see that the control ball stress and stress ratio remain the same. The body strain analysis of the original sample and the remodeled sample shows that there is a positive correlation between the initial water content and the volume strain. It is determined that the ball stress and the initial water content remained the same. Under the same conditions of stress ratio, the body strain of the original sample is significantly smaller than the body strain of the reshaped sample. At the same time, we can see that the bulk strain of the undisturbed sample and the remolded sample has a negative correlation with the stress ratio. In the analysis of spherical stress and bulk strain of undisturbed samples, the existence of structural strength at the beginning will make the relationship between stress and strain linear, then the compression will gradually deepen. The structure
of the samples will gradually be destroyed, and the relationship between stress and strain will show approximate plasticity. Even if a slight increase in stress will cause increased deformation; finally, the stress continues to increase, and the secondary structure inside the samples will gradually increase, and the entire deformation process tends to be stable. The ball stress and body strain of the remodeled loess are analyzed.[5-7] According to the analysis of the curve, the stress gradually increases, the sample is gradually compressed, and the stress and strain also shows a linear relationship. Subsequently, the stress is gradually increasing, and the deformation will be gradually deepened and will tend to a certain value. If the stress is relatively small, the shear deformation will gradually form as the stress increases, so the deformation with shear cracks can be observed on the sample, and then it is gradually destroyed.

Fig. 1 Stress-strain curves of undisturbed and remolded loess under different stress conditions

In Figure 2, the undisturbed saturated loess samples under different stress ratios are studied. The curves of spherical stress and volume strain are similar to those of remolded samples, which can also be divided into compaction stage and denaturing stable stage. Immersion will make the structure of the sample gradually changed, and the increase of stress will make the water in the pores of the sample gradually compacted. When the stress continues to increase, the deformation will gradually tend to a stable value.[8-10]
Figure 3 is the stress-strain test curve of undisturbed loess with different initial water content under the same stress ratio. In the figure, it is obvious that under the same stress state, and the volume strain and water content show a positive correlation. Under the condition of $k = 0.75$, the ball stress is set as 220KPa test specific value, and it is found that $w = 4\%$, volume strain is 1.5%; $w = 17.5\%$, volume strain is 6%. The inflection point of the spherical stress and body strain curve is taken for research, and the corresponding value of the inflection point is set to the strength of the structural failure under the stress state. We make statistics on the relationship between the specific structural failure strength and the initial water content, and get Figure 4. It is found that the degree of structural strength failure of the sample decreases obviously with the increase of water content, and the state of power function appears between the structural strength and water content. It may be due to the fact that the water content of structural strength increases and decreases rapidly, so that when the water content is low, the decrease is relatively higher than that of the higher water content.
(2) The characteristics of the structural change of loess are studied based on the results of constant stress ratio tests.

According to Figure 5, we can observe that under the same conditions of spherical stress, the stress ratio and structural parameters show an inverse relationship, that is, the smaller the stress ratio is, the stronger the tendency of the instability of the loess structure is. It is easier to destroy the structure. On the other hand, the structural parameters and ball stress show an inverse relationship. Under different stress ratio states, the structural parameters finally show a stable trend at the same level, which suggests that after the structure of the highly stressed loess is damaged, the structural parameters have no more sensitive manifestation of the stress change in the corresponding state. According to the analysis in Figure 6, the water content and structural parameters show an inverse relationship under the effect of spherical stress. The lower the water content is, the greater the impact of structural parameters is, so the water content has a great impact on structural parameters.[11, 12]
Fig. 5 Change curve of different structural parameters of stress ratio

Fig. 6 Variation curve of different structural parameters of initial water content

(3) The structural stress-strain of the loess is studied under the constant stress ratio test structure. It can be seen from Figure 7 that the structural strain and stress present a double-sided curve compared with the undisturbed loess, and the structural parameters show a normalized effect on the deformation surface of the undisturbed loess. As a result, the moisture and viscosity of the soil sample can be more
comprehensively presented in numerical form. Figure 8 is the change curve of unsaturated loess under different stress conditions. If the intercept is \( b \) and the slope is \( a \), there will be a trend chart of stress change between \( a \) and \( b \), which will be sorted into Table 2.

![Figure 7](image7.png)

**Fig. 7** Change curves of structural strain and stress

![Figure 8](image8.png)

**Fig. 8** Change curve of unsaturated loess under different stress conditions

| Parameters | \( K=0.25 \) | \( K=0.5 \) | \( K=0.75 \) | \( K=1 \) |
|------------|--------------|--------------|--------------|------------|
| a          | 0.1564       | 0.0956       | 0.0685       | 0.0498     |
| b          | 0.0435       | 0.0467       | 0.0374       | 0.0343     |

**Table 2.** Test parameters of unsaturated loess under different test conditions

3. **Detailed analysis from the stress elastic-plastic constitutive model of unsaturated soils**

From the perspective of constructing the constitutive model, it is necessary to determine the initial yield curve and yield function, make sure the loading function, and then verify the constructed constitutive function to determine its feasibility. The relationship between the initial hardening parameter \( h_0 \) and the initial water content \( w \) of the unsaturated loess is calculated from equation 1.
The loading function considers the determination of the hardening parameter value $h_f$ from the average stress value $P_f$ and the stress ratio $n_f$ at failure, which can be seen in equation 2.

$$h_0 = 3.4934 w^{-0.4571} \quad (1)$$

$$h_f = P_f \exp \left( \frac{n_f}{2.1} \right)^{1.5} \quad (2)$$

During the verification, we can analyze the calculation results and test results of the structural loess under different consolidation confining pressures. Figure 9 shows that the calculation results of the model and the test results are consistent. Therefore, the elastic-plastic constitutive model of unsaturated loess established in this study is scientific and effective, and can show the strain characteristics of the soil. On the other hand, when the confining pressure and water content are large, the degree of agreement of the hardening simulation of the peak front of the unsaturated soil is high. However, when the confining pressure and water content are small, it shows a certain mismatch. But in general, the effect of this simulation is ideal, and it can support the experimental viewpoint of this demonstration.

![Fig. 9 Comparison of calculation results and test results under different consolidation confining pressures](image)

**Fig. 9** Comparison of calculation results and test results under different consolidation confining pressures

4. Conclusion
Through the final model construction and demonstration of the design scheme and analysis results, it is found that there is a certain difference between the undisturbed loess and the remolded loess. The stress-strain curve of undisturbed loess shows the process of approximate elastic deformation and plastic deformation, while that of remolded loess is the stage of compaction and deformation. With the increase of water content, the volume strain of stress shows inverse correlation, and the contrast between stress and $K$ is small. In addition, the elastic-plastic constitutive model of unsaturated loess can be established by selecting the appropriate hardening parameters, and the stress-strain characteristics can also be obtained by simulating the unsaturated loess under different confining pressures and initial perspiration rates.

References
[1] Chen Fei, Shao Shengjun, Shao Shuai. *Experimental Study on the Initial Yield and Strength*
Characteristics of Loess Based on Strain Energy [J]. Journal of Rock Mechanics and Engineering, 2017 (A02): 4151-4157.

[2] Zhan Liangtong, Hu Yingtao, Liu Xiaochuan. Centrifugal Model Test of Rainfall Infiltration in Unsaturated Loess Foundation and Joint Monitoring of Multiple Physical Quantities [J]. Geotechnical Mechanics, 2019 (7).

[3] Li Wei, Zhuang Jianqi, Wang Ying. Experimental Study on Influencing Factors of Shear Strength of Saturated Remolded Loess [J]. Journal of Engineering Geology, 2018, 26 (3): 626-632.

[4] Xue Bowen, Li Tonglu, Deng Lejuan. Determination of Strength Parameters of Unsaturated Loess on the South Bank of Jingehe River [J]. Journal of Gansu Science, 2019 (3).

[5] Li Tao, Jiang Mingjing, Zhang Peng. Three Dimensional Discrete Element Analysis of Unconfined Compression and Collapse Test of Unsaturated Structural Loess [J]. Journal of Geotechnical Engineering, 2018, 40 (S1).

[6] Zhu Zhikun, Tong Fei. Influence of Dry Density and Moisture Content on Strength and Strength Parameters of Taiyuan Remolded Loess [C] // 2018 National Academic Conference of Industrial Buildings.

[7] Zhen Ziqiang. Simulation of Soil Moisture and Analysis of Water Availability in the North Warping Dam Area of the Loess Plateau: Taking Liudaogou Watershed as an Example [D]. 2017.

[8] Feng Yongzhen, Zhang Wuyu, Ma Yanxia. Study on Deformation of Remolded Loess under Rotation of Principal Stress Axis Considering the Influence of Deviator Stress Ratio [J]. Journal of Disaster Prevention and Mitigation Engineering, 2018 (3).

[9] Xu Jie, Zhao Wenbo, Chen Yonghui. Experimental Study on Initial Shear Modulus and Pore Size Distribution of Unsaturated Loess [J]. Journal of Geotechnical Engineering, 2016, 39 (S1).

[10] Guo Nan, Yang Xiaohui, Chen Zhenghan. Influence of Matrix Suction on Strength and Deformation Characteristics of Undisturbed Unsaturated Loess [J]. Journal of Lanzhou University of Technology, 2017 (6): 120-125.

[11] Shao Shengjun, Chen Fei, Deng Guohua. Study on Passive Earth Pressure of Structural Loess Filler Retaining Wall Based on Plane Strain Unified Strength Formula [J]. Geotechnical Mechanics, 2019 (4).

[12] Zhou Mingru, Xiao Yongzhan, Lu Guowen. Analysis of Large Deformation of Unsaturated Loess in Longdong [J]. Industrial Building, 2019 (4).