Study on the strength and deformation characteristics of loess under multi-staged unloading

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ABSTRACT

The strength and deformation characteristics of loess under vertical unloading path is important for the study of slope instability in excavation area. From the perspective of engineering application, direct shear test is carried out. Moreover, a discrete element method model is established to study micro-mechanism of multi-stage unloading. It is found that the shear displacement-shear stress curve of the soil under the multi-stage unloading path is different from those under the loading state. The soil sample is prone to shear failure during small deformation under multi-stage unloading. The shear strength is related to the initial consolidation pressure and unloading ratio. During the multi-staged unloading process, the number of contacts between particles does not change significantly, while the contact forces between particles decrease obviously.

Key words: multi-staged unloading, shear displacement-shear stress, shear strength, discrete element method

1 INTRODUCTION

Many geohazards in China occur in the Loess Plateau resulting in human loss, damage of gas and oil routes, destruction of roads and railways, as well as reduction in farmlands(Tu et al., 2009; Derbyshire et al., 1994; Zhuang et al., 2018; Wang et al., 2018). At present, a series of large-scale excavation and filling projects are adopted to improve the environment of these disaster area. Field investigation of large-scale excavation and filling projects shows that the frequency of landslides in the excavated area is increasing with time while the filling area is stable (Fan et al., 2019; Pu et al., 2016). Fig. 1 shows a slope in the excavation area and its internal one-point stress state. It’s obvious that this stress state changes from the original stable to the unloading stress state. The unloading stress state can be divided into vertical and lateral unloading (Shi et al., 2016; Zhang et al., 2013). Vertical unloading can be further divided into nonlinear continuous unloading and multi-stage unloading according to unloading process.

The stress path of the actual excavation is very complicated. Simplified methods were used by researchers to investigate the influence of the unloading stress path on the mechanical characteristics of soil. Based on excavation path of foundation pits, Zhuang et al. (2009) and He et al. (2005) conducted undrained lateral unloading test using a true triaxial apparatus and found that the soil collapsed under a small strain. Zhang et al. (2017, 2015) carried out the lateral unloading test for undisturbed loess under plane strain conditions. The results show that the failure strain is much smaller than that of plane strain loading and conventional triaxial test. Discrete element simulation for the different unloading stress path was also carried out by Zhang and Jiang (2018). Cheng (2000) and Zhao et al. (2018) used the direct shear apparatus to study the strength characteristics of the unloading soil. It is found that the shear strength under unloading condition is affected by the unloading ratio and the pre-consolidation pressure. Moreover, based on excavation path of tunneling, both theoretical and numerical models were presented for considering unloading response by Li et al. (2014) and Zhao et al. (2014). Compared with excavation path of foundation pits, violent failure of rocks is more involved into the unloading path of tunneling. In addition, Ng (1999) and Li et al. (2014) have also studied the stress path changes during unloading.

The above discussion suggests that the existing researches mainly focuses on the lateral unloading involved in excavation of foundation pits and tunneling.
and conventional triaxial test is mostly applied. However, compared with the excavation of foundation pits and tunneling, large-scale excavation involves more vertical unloading, which is different from the excavation of foundation pits and tunneling. Therefore, it is of great importance to study the strength and deformation characteristics of loess slope formed due to large-scale excavation and filling works.

Based on the unloading process, the vertical unloading can be divided into two forms. One is nonlinear continuous unloading, the other is multi-staged unloading, as shown in Fig. 2. In nonlinear continuous unloading, the normal stress decreases continuously and nonlinearly during an excavation operation. While in multi-staged unloading, the normal stress decreases with the unloading stage. Generally, the landslides of the excavation slope often occur in the continuous unloading process. However, multi-staged unloading is critical to the long-term stability of the slope. Therefore, it is of practical value to study the strength characteristics of loess during the multi-staged unloading.

The main objective of this paper is to study the strength and deformation characteristics of loess under multi-staged unloading. From the perspective of engineering application, direct shear test is carried out.

To describe the effect of multi-stage unloading, the unloading ratio between initial consolidation pressure and normal stress was defined by researchers (Zhao et al., 2018; Pan et al., 2001):

$$R = \frac{\sigma_n - \sigma'_n}{\sigma_n} = \frac{\Delta \sigma_n}{\sigma_n}$$

where $\sigma_n$ is initial consolidation pressure, $\sigma'_n$ is normal stress.

Table.2 Specific multi-stage unloading condition.

| $\sigma_n$ /kPa | Code  | $\sigma'_n$ /kPa | Unloading ratio |
|----------------|-------|-----------------|-----------------|
| 200            | B1-1  | 200             | 0.00            |
|                 | B1-2  | 100             | 0.50            |
|                 | B2-1  | 300             | 0.00            |
| 300            | B2-2  | 200             | 1/3             |
|                 | B2-3  | 100             | 2/3             |
|                 | B3-1  | 400             | 0.00            |
| 400            | B3-2  | 300             | 0.25            |
|                 | B3-3  | 200             | 0.50            |
|                 | B3-4  | 100             | 0.75            |

The soils were recovered from a loess platform on the south bank of Jinghe River in Jingyang city, Shanxi Province. Fig. 2 presents the particle size distribution of the loess. The physical parameters of the soil samples are shown in Table 1.
Three initial consolidation pressures of 200 kPa, 300 kPa, and 400 kPa were selected to perform the vertical multi-staged unloading direct shear test. The designed initial consolidation pressure is applied to the soil sample in the shear box by the weight to make it fully drained and consolidated. After the soil sample consolidated and stabilized, reduce the weights to achieve that the normal pressure acting on the soil sample is unloaded to the required normal stress. The specific multi-stage unloading condition is shown in Table 2. Corresponding to this scheme, the total stress path is shown in Fig. 4. The test was carried out using a shear rate \( \gamma = 0.8 \text{ mm/min.} \)

To study the micro-mechanism under multi-stage unloading, the numerical model was established using discrete element method, as shown in Fig. 5. The model size was 61.8 mm \( \times \) 20 mm that is consistent with indoor direct shear experiments. The radius of particles obeys a uniform distribution, \( R_{\text{max}} = 0.08 \text{ mm}, R_{\text{min}} = 0.03 \text{ mm.} \) The linear contact model is selected. The parameters are shown in Table 3.

Table 3 Mechanical parameters of numerical simulation

| Wall    | Particle |
|---------|----------|
| normal stiffness | Shear stiffness |
| N.m\(^{-1}\) | N.m\(^{-1}\) |
| 5 \times 10\(^7\) | 0 |
| density | Normal-to-shear stiffness ratio |
| kg.m\(^{-3}\) | N/m\(^2\) |
| 2670 | 1.333 |
| effective modulus | Fricction coefficient |
| N/m\(^2\) | |
| 1 \times 10\(^9\) | 0.7 |

Fig. 5 Numerical model

3 RESULTS AND DISCUSSIONS

3.1 Deformation characteristics

It is worth noting that in the direct shear test, the distribution of shear stress and shear displacement of the specimen is not uniform, so the relationship between shear stress and shear displacement on the shear plane can only be obtained by direct shear test. The data of the samples B1-1~2, B2-1~3, and B3-1~4 measured by the direct shear test are sorted, and the corresponding shear stress (\( \tau \))-shear displacement (\( \delta \)) relationship curve is plotted, as shown in Fig. 6.

It shows that the shear stress increases with the increase of shear displacement. Wang et al. (2014) described the relationship between shear stress and shear displacement using a hyperbolic model. Good results have been achieved. Therefore, the shear stress-shear displacement can be considered by hyperbolic relationship. When the initial consolidation pressure is equal to 200kPa, 300 kPa and 400 kPa, under the multi-stage unloading condition, the shear stress-shear displacement curves are basically coincident when the shear displacement is relatively small. However, when shear displacement increases to a certain value, the influence of unloading on the shear stress-shear displacement curve begins to be prominent. The greater the unloading ratio, the more obvious the influence.

Compared with the loading condition (\( R = 0 \)), the shear
displacement, corresponding to the peak strength, is significantly reduced under multi-stage unloading. The greater the initial consolidation pressure is, the more significant the shear displacement decreases. This phenomenon indicates that the soil sample is also prone to shear failure during small deformation under multi-stage unloading.

### 3.2 Strength characteristics

The effect of stress path on the relationship between shear displacement and shear stress is also analyzed, as shown in Fig. 7.

It’s obvious that the soil is transformed from normal consolidation to over-consolidation by unloading. The larger the unloading ratio, the larger the over-consolidation ratio. When the normal stress is the same, the peak strength increases as the initial consolidation pressure increases. The effect of initial consolidation on peak strength decreases as normal stress decreases. There are only two curves when initial consolidation pressure is equals to 200 kPa, so the shear strength envelope cannot be plotted. The peak strength and normal stress under different paths are shown in Fig. 8.

It can also be seen from Fig. 8 that for the multi-staged unloading, when the initial consolidation pressure is 300 kPa, the peak shear stress during the unloading process is always below the loading strength envelope. However, as the initial consolidation pressure increases to 400 kPa, when unloading ratio R=0.25, the peak strength is above the loading strength envelope, and as the unloading ratio increases, the peak strength is below the loading strength envelope. Therefore, it can be concluded that the shear strength is related to the initial consolidation pressure and unloading ratio under multi-staged unloading condition. This is consistent with conclusions conducted by Zhao et al. (2018).

![Fig. 7 Effect of stress path on the relationship between shear displacement and shear stress](image)

![Fig. 8 Relationship between peak strength and normal stress under different unloading paths](image)

### 3.3 Micro-mechanism of multi-stage unloading

![Diagram](image)
To study the micro-mechanism of multi-stage unloading, distribution of normal and shear contact number under different unloading ratio are plotted, as shown in Fig. 9. It shows that the number of contacts between particles does not change significantly during the multi-staged unloading process. However, the contact forces between particles decrease obviously.

4 CONCLUSIONS

In this paper, the deformation and strength characteristics of loess under vertical multi-stage unloading is studied, the following conclusions are obtained:

(1) The relationship between the shear displacement and shear stress under vertical multi-staged unloading soil is hyperbolic and the shear displacement, corresponding to the peak strength, is significantly reduced under multi-stage unloading;
(2) The shear strength is related to the initial consolidation pressure and unloading ratio under multi-staged unloading conditions;
(3) During the multi-staged unloading process, the number of contacts between particles does not change significantly, while the contact forces decrease obviously.

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