Sensitivity Analysis of Loess Triaxial Mesoscopic Parameters Based on PFC\textsuperscript{3D}

Baohua Cao\textsuperscript{1}

\textsuperscript{1}Chang’an University, School of Highway, Xi’an, Shaanxi, 710064, China; Corresponding author’s e-mail: 1220825132@qq.com

Abstract: Based on PFC\textsuperscript{3D} software and theory, combined with the indoor triaxial test results to calibrate the basic micro parameters of numerical simulation, through a large number of literature reading, respectively, the friction coefficient, porosity, particle size distribution are determined as the sensitivity factors affecting the triaxial numerical simulation of loess. The conventional triaxial numerical simulation of loess numerical samples under 200kPa confining pressure was conducted. The sensitivity analysis of meso-parameters is carried out by changing the degree of influence of meso-parameters such as the minimum particle radius on the macro-mechanical behavior of loess numerical samples, and the relationship between micro parameters of soil and macro mechanics is established. The results show that the order of the influence of particle mesoscopic parameters on peak strength is as follow: porosity $>$ friction coefficient between particles $>$ particle size distribution; the order of influence on residual strength is as follow: porosity $>$ friction coefficient between particles $>$ particle stiffness ratio $>$ particle size distribution; the order of influence on the initial linear elastic modulus of the loess material is as follow: porosity $>$ friction coefficient between particles $>$ particle size distribution; the order of effect on softening characteristics is as follow: porosity $>$ friction coefficient between particles $>$ particle size distribution.

1. Introduction

Loess is widely distributed in Northwest, North, and Northeast in China. The stress-strain curve obtained through the laboratory triaxial test is the main method to study the shear strength of the loess. Through a large number of experiments, the PFC\textsuperscript{3D} software can effectively carry out the triaxial test. The calibration of mesoscopic parameters of the three-axis numerical simulation of loess is a complicated process. In order to obtain the mesoscopic parameter values that are highly consistent with the results of the laboratory test, it is necessary to carry out a large number of trial operations, and because of the different mesoscopic parameter adjustment methods in the discrete element particle flow model, sometimes the same macro-mechanical stress-strain curve is obtained, so the particle flow sensitivity analysis of the triaxial test is the key to the reasonable selection of discrete element meso parameters and whether the discrete element mesoscopic simulation can truly reflect the dynamic behavior of the soil, which can greatly reduce the calculation amount of trial.

Williams and Rege[1](1997) conducted particle flow simulations of biaxial compression tests on particles of different shapes. The results show that the particle shape is closely related to the compressibility of the material. Bagherzadeh-Khalkhali[2](2009) studied the effect of the maximum particle size of coarse-grained soil on shear strength. Liu, J., et al.[3] found that by changing the microstructure of the particles, it had a significant effect on the macroscopic mechanical behavior of the material. Tang, W.S.[4] conducted a discrete element numerical simulation analysis of coarse sand
in Qingdao based on the two-dimensional particle flow PFC\textsuperscript{2D}. The results show that the meso-parameter friction coefficient and particle size have a greater influence on the softening of coarse sand. Geng. Li.[5] conducted a triaxial particle flow consolidation drainage test on coarse-grained soil in the dump, and found that the strength of the coarse-grained soil increased with the increase of the friction coefficient between the particles and the bonding strength at the contact. The resistance of the particle shape to the material effect of shear strength is significant. Luo, Y., et al.[6] conducted a large number of particle flow numerical experiments to study the engineering mechanical properties of sand from a meso-mechanical perspective, and revealed that the friction coefficient and porosity between soil particles have obvious effects on the macroscopic mechanical behavior of the material. Li, S.B. et al[7] carried out CU meso numerical simulation on loess in Longxi area. The results show that the normal stiffness of the particles controls the macroscopic deformation modulus, the ratio of the normal stiffness to the tangential stiffness controls the Poisson's ratio, and the friction factor controls the peak strength. The bond strength controls the cohesive strength in the shear strength at different water contents. Liu, Y., et al[8] studied the effect of friction coefficient, meso-connection strength and porosity on the macro-mechanical properties of the sample particles based on the triaxial test results of a coarse-grained soil, and the effect of the meso parameters of the model on the macro-mechanical response is revealed.

At present, some scholars' research based on the triaxial numerical experiment in the particle flow laboratory mainly focuses on the regularity of the mechanical properties of non-cohesive soils such as sand, coarse-grained soil. It is concluded that PFC\textsuperscript{3D} is not used to systematically analyze the sensitivity of various mesoscopic parameters to the macro mechanics and deformation characteristics of loess. Therefore, by adjusting the values of the mesoscopic parameters, the three-dimensional mesoscopic analysis is carried out from the micro perspective to find out the relationship between the mesoscopic parameters and the macro mechanical properties of loess, and further study the triaxial simulation analysis of loess the calibration principle of mesoscopic parameters. Further research on the degree of influence of mesoscopic parameters on the macro-mechanical properties and deformation sensitivity of loess is of great significance to the establishment of a loess mechanical model.

2. Particle flow numerical simulation of loess triaxial test

2.1. Model establishment

The numerical simulation analysis of the test uses a linear contact model. The establishment of the model is divided into two steps: ① setting a cylinder model that conforms to the actual structure to constrain the bulk structure, the initial size high is 0.08m and the diameter is 0.0391m; ② the test granular sample is established. The loess structural system is composed of skeleton particles, the actual sample particles are thousands, and the calculation model is difficult. To reduce the calculation amount, the radius enlargement method is used, so the particle size is set to 7e-4~17e-4, and evenly distributed.

The bonding relationship between the particles adopts the contact bonding method. The three-axis calculation model is shown in Figure 1.

2.2. Selection of basic parameters of triaxial model

According to the results of the indoor triaxial test, the maximum partial stresses of the samples under different confining pressures of 50kPa, 100kPa, 150kPa, and 200kPa are 142.8kPa, 207.9kPa, 290.0kPa, and 353.2kPa. Calculate the radius of the mohr circle and the abscissa of the center of the mohr circle according to formulas (2-1) and (2-2). The molar stress circle is shown in Figure 2 below.

From the shear strength formula and the mohr circle fitting tangent formula in Figure 2 below, the cohesive force \(c=24.09\)kPa, \(\tan\varphi=0.45\), and the friction angle \(\varphi=24^\circ\).

\[
p = \frac{1}{2} (\sigma_1 - \sigma_3)
\]  

(2-1)


\[ q = \frac{1}{2} (\sigma_1 - \sigma_3) \quad (2-2) \]

3. Sensitivity analysis of the triaxial mesoscopic parameters of loess

There are many factors that affect the shear strength and deformation of the triaxial model test. According to the relationship between the shear strength of soil in advanced soil mechanics[9] and its influencing factors, it can be determined as the following formula:

\[ \tau_f = f(e, c, \phi, C, \sigma, T, H, \varepsilon, \dot{\varepsilon}, S, v) \quad (3-1) \]

The factors that affect the shear strength and deformation of soil can be divided into two categories: one is the physical properties of the soil itself, such as the porosity \( e \) in the formula, the composition of the soil \( C \), the adhesion \( c \) and friction angle \( \phi \) of the soil, etc. The other type is external conditions, such as the temperature \( T \) in the above formula, the confining pressure range \( \sigma \), the stress history \( S \), the drainage condition \( H \), and the loading rate \( v \). These external factors mainly affect the strength of the soil by changing the physical properties of the soil.

The model sample generated based on the discrete element theory does not exist stress history, temperature and other concepts. Combined with the inherent parameters in the discrete element model, this paper aims at the following mesoscopic parameters on the shear strength and deformation of loess sensitivity analysis of the impact, based on the results of laboratory tests as basic calculation parameters, respectively study the general laws of the mesoscopic parameters on the macro mechanical properties and deformation of the loess, and provide some reference for the adjustment of PFC3D simulation parameters in the future triaxial test. Mesoscopic parameters include friction coefficient, porosity, particle size distribution.
3.1. Friction coefficient
Taking the coefficient of friction as a variable and the basic parameters obtained from laboratory tests as invariants, the friction coefficient values are set to 0.35, 0.45, 0.55, 0.65 under the confining pressure of 200kPa. The influence of friction coefficient on the stress-strain curve of loess is shown in Figure 3, and the influence curve of peak strength and residual strength is shown in Figure 4. As shown in Fig.4, the peak strength of the loess numerical samples shows an increasing trend with increasing friction coefficient, and the increasing trend is not obvious, showing a positive correlation. This phenomenon can be understood as: due to friction between loess particles increase of the coefficient will increase the frictional strength of the soil (including the sliding friction and occlusal friction of the particles), thereby increasing the frictional force at the contact of the particles and the interaction between the particles, making the particles move, rotate and slide. As the friction coefficient increases, the peak strength of the sample gradually increases, and the remaining strength increases slowly when the friction coefficient is small. In the three-dimensional discrete element, when a shear band is formed in the sample, the particles will squeeze and move, but they will not separate. At the same time, due to the existence of confining pressure, the contact force between the particles is caused by friction and side contact force and the vertical contact force are composed, so the factors affecting the remaining strength in the three-dimensional discrete element model are not only the friction coefficient.

![Figure 3. Effect of friction coefficient on stress-strain curve (200kPa)](image1)

![Figure 4. Effect of friction coefficient on peak strength and residual strength](image2)

In summary, taking the basic friction coefficient 0.45 obtained in this test as a reference, when the friction coefficient increases from 0.45 to 0.55, the peak shear strength increases from 251.18kPa to 267.15kPa, the increase is 6%, and the remaining shear strength from 203.73kPa to 223.48kPa, the increase is 8.84%, so the friction coefficient has little effect on the loess peak shear strength and residual strength.

3.2. Porosity
Porosity is one of the important factors affecting the shear strength and deformation of loess. In this paper, based on the indoor triaxial test, under the condition of confining pressure of 200kPa, the triaxial numerical simulation tests with porosities of 0.25, 0.35, 0.45, and 0.55 were set respectively, and the stress-strain curve is shown in Figure 5. The results show that when other parameters remain unchanged, when the porosity changes within a certain range, with the increase of the sample porosity, the peak strength of the sample decreases significantly, and the stress-strain curve of the loess gradually from the strain softening type when the porosity is low to the strain hardening type when the porosity is high. When the porosity is small, the sample exhibits brittle failure during shear failure. When the porosity is 0.45, the sample shows a significant body shrinkage effect[8]. The fitting curve
of peak intensity and porosity is shown in Figure 6. According to different porosity, different peak shear strengths of samples are obtained. The relationship between them is as follows:

\[ \sigma_p = 668.565 - 890.082 \times n \]  

(3-2)

Therefore, the porosity has a greater influence on the peak shear strength and residual strength of the loess. When the porosity increases from 0.25 to 0.35, the peak shear strength decreases from 456.83kPa to 349.04kPa, a decrease of 23.4%. The residual strength is reduced from 292.68kPa to 250.25kPa, the reduction is 14.5%, and the impact on the peak strength of the material is greater than the residual strength.

### 3.3. Particle size distribution

Taking the basic parameters obtained from laboratory experiments as invariants, changing the particle size distribution range, as shown in Table 3 below, a three-axis simulated shear test was conducted under a confining pressure of 200kPa. The stress-strain curves under different minimum particle size conditions are shown in Figure 8.

As shown in Figure 7, when the minimum particle size of the sample is 0.7mm, the particle displacement field distribution area is more obvious at the end of the shear. The upper particles move more to the left and the lower particles move more to the right. The particle displacement field is divided into two blocks. With the increase of the minimum particle size, the distribution of this
particle displacement field is less obvious, especially when the minimum particle size is 1mm, the particle size in the model sample is not much different, and most particles move downward. The sample blocking phenomenon is not obvious.

The results of this simulation are shown in Figure 8. With the increase of the minimum particle size, the impact on the peak shear strength and residual strength of the model sample is small, and strain softening occurs. The reason for the preliminary judgment is that when the smallest particle size is smaller, when the numerical model is generated, the particles with the smaller particle size exist in the gap with the larger particle size, and the bite between the particles is tighter, especially after loading for a period of time. After squeezing and misalignment, the fine particles play a good "plug gap" between the large particles, which is conducive to the transmission of contact force and the generation of friction.

Table 2. Determination of the minimum particle radius and maximum particle radius ratio

| Rmin (mm) | Rmax (mm) | ratio (min/max) | Number of particles |
|-----------|-----------|-----------------|---------------------|
| 0.7       | 1.7       | 2.429           | 7164                |
| 0.8       | 1.6       | 2.000           | 6983                |
| 0.9       | 1.5       | 1.667           | 7321                |
| 1.0       | 1.4       | 1.400           | 7559                |

In summary, when the minimum radius is increased from 0.7mm to 0.8mm, the peak intensity decreases from 251.69kPa to 243.87kPa, the decrease is 3.02%, and the residual intensity decreases from 201.82kPa to 203.79kPa, the increase is 1%, the particle size distribution has a relatively small effect on the peak shear strength and residual strength of the sample.

4. Conclusion

1. As the friction coefficient between particles increases, the strain softening characteristics increase, and the peak strength of the loess numerical samples shows an increasing trend under 200kPa confining pressure, and the increase trend is not obvious, showing a positive correlation, the remaining strength increases slowly when the friction coefficient is small. And the initial linear elastic modulus of the loess sample material is basically not affected by the friction coefficient of its meso-particles.

2. When the porosity changes within a certain range, the peak shear strength of the sample decreases significantly with the increase of the porosity of the sample, the stress-strain curve of loess gradually develops from the strain softening type when the porosity is low to the strain hardening type when the porosity is high, which has a greater influence on the peak strength of the material than the residual strength.

3. With the increase of the minimum particle size, the impact on the peak shear strength and residual strength of the model sample is small, and strain softening occurs. When the minimum particle size of the sample is 0.7mm, the distribution area of the model sample particle displacement field is divided into two pieces at the end of the shear. When the minimum particle size is 1mm, the particle size in the model sample is not much different, most particles move downward, the sample blocking phenomenon is not obvious.

4. In this paper, the sensitivity analysis of the influence of friction coefficient, porosity and particle size distribution on the shear strength and deformation of loess numerical samples is conducted. The order of the effect of the mesoscopic parameters of the particles on the peak strength is as follow: porosity>friction coefficient between particles>particle size distribution; the order of the effect on the remaining strength is as follow: porosity>friction coefficient between particles>particle size distribution; the order of influence on initial linear elastic modulus of loess material as follow: porosity>friction coefficient between particles>particle size distribution; the order of influence on softening characteristics is as follow: porosity>coefficient of friction between particles>particle size distribution.
Acknowledgements
This work was partially supported by the National Key R&D Program of China (No. 2016YFC0802203-8), Supported by the Fundamental Research Funds for the Central Universities, CHD (No.300102219213), Project Mechanism of mega loess slope sliding supported by NSFC (No.41790443), Key R&D Program of Shaanxi Province (2018ZDXM-SF-024).

References:
[1] Williams JR, Rege N. (1997) The development of circulation cell structures in granular materials undergoing compression[J]. Power Technology, 90:187-194.
[2] Ahad B.K., Mirghasemi A. A. (2009) Nu-merical and experimental direct shear tests for coarse-grained soils[J]. Particuology, 7(1):83-91.
[3] Liu, J., Sun, T., Zhang, Y.X., et al. (2015) Mesoscopic discrete element simulation of different sizes of sand [J]. Journal of Beijing University of Civil Engineering and Architecture, 2016, 32(04):18-23.
[4] Tang W.S.. Influence of discrete element mesoscopic parameters on deformation properties of coarse sand [J]. Water Conservancy Science and Technology and Economy, 21(02):32-34.
[5] Geng L., Huang Z.Q., Miao Y. (2011) Mesoscopic simulation of coarse-grained soil triaxial test [J] Journal of Civil Engineering and Management, 28(04):24-29.
[6] Luo, Y., Gong, X.N., Lian, F. (2008) Simulation of mechanical behaviors of granular materials by three-dimensional discrete element method based on particle flow code [J]. Chinese Journal of Geotechnical Engineering, 2008, 30(02):292-297.
[7] Li, S.B., Wang, C.M., Wang, N.Q., et al. (2013) Numerical simulation of particle flow in triaxial test of loess [J], China Journal of Highway and Transport, 26(06):22-29.
[8] Liu, Y., Zhu, J., Yan, B. (2014) Meso-mechanical simulation study on triaxial test of coarse-grained soil based on DEM[J], Journal of Railway Science and Engineering, 11(04):58-62.
[9] Xie, D.Y., Yao, Y.P., Dang, F.N. (2008) Advanced soil mechanics[M]. Higher Education Press, Beijing.