DEM analyses of true triaxial and wetting tests on unsaturated structural loess

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ABSTRACT

Three-dimensional DEM (discrete element method) simulations of the true triaxial and wetting tests were conducted to study the macroscopic and microscopic mechanical properties of unsaturated structural loess under complex stress state. The simulation results were analyzed in terms of stress-strain relationships, void ratio responses and bond breakage number with water content. It is shown that collapsing failure occurs when the deviatoric stress approaches or exceeds the peak shear strength of the corresponding saturated structural loess sample. There is little difference in the axial strain between the quick wetting (QW) method and gradual wetting (GW) method, and the volumetric strain of the samples wetted by QW are larger than that by GW specimen. The bond breakage number of the sample wetted by QW is slightly higher than that by GW. However, the bond breakage number of the sample wetted by the two wetting methods is slightly higher than that of the saturated structural loess sample subjected to the same stress state.

Keywords: loess, wetting test, true triaxle test, collapsibility

1 INTRODUCTION

Natural loess is a type of special structural and collapsible soil mainly composed of micron scale particles (Wang et al., 2019). It shows high shear strength when the macro-void and cementation structure is not broken. However, when water content is increased in natural loess, the interparticle bond will rapidly break down, and the soil skeleton, especially trellis pores will promptly collapse. At the same time, the strength will suddenly decrease drastically and the deformation will be greatly accelerated, which may lead to various geological disasters. (Liu et al., 2015; Xie et al., 2018; Lal, 2019).

Most of the experimental researches on loess collapsibility are preformed via one-dimensional (1D) compression tools. However, these tests are only suitable for solving the problem of collapsibility in large-scale ground under uniform loads. When the ground is subjected to non-uniform loads, the deformation predicted by conventional compression and wetting tests may differ from the practical situation (Lawton et al., 1991). Therefore, the mechanical response should be taken into account in predicting the collapsible deformation (Xie, 2001). In the previous studies on collapsibility of loess under complex stress state, Chen et al.(2001) indicated that the intact loess wetted to saturating mainly exhibited the relationship between deformation and the principal stress: it mainly exhibited volumetric deformation when the principal stress was relatively large, and it mainly exhibited shear deformation when the principal stress was relatively small. 1D collapsibility tests on loess under different pressure conditions and triaxial collapsibility tests on loess under different stress ratios were studied by Lawton et al. (1989, 1991, 1992), which indicated that the loess dilated under 1D low pressure and collapsed under high pressure; in the triaxial tests, the axial strain and lateral strain were related to the mean stress and stress ratio. Jiang et al. (1998a, 1998b, 2012) performed triaxial wetting tests on artificial structural loess under different deviatoric stress level \( (R_v=q/q_{peak}) \), which indicated that the collapsible deformation developed nonlinearly with the water content, and the concept of initial collapse surface was proposed in \( p-q \) space. Great efforts have been made on the wetting methods of loess specimen by quick wetting to saturating, but there were few studies on the wetting method of loess specimen by gradual wetting. Xie (2001) figured out that the loess ground was difficult to reach full

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saturation in engineering (especially in some loess areas with deep groundwater level and low rainfall), and suggested further research on the evolution of loess collapsibility in gradual wetting.

Laboratory tests are widely used in the study of mechanical properties of structural loess, and the studies of wetting tests usually focus on 1D compression test and conventional triaxial test. In practical engineering, however, the loess may be in a certain water content within a complex three-dimensional (3D) stress state. Therefore, it is necessary to further carry out the true triaxial and the wetting tests on unsaturated structural loess. However, due to the reproducibility of natural structural loess samples, the wetting test under complex stress is difficult to operate in laboratory tests. At the same time, due to the expensive and complicated true triaxial test equipment, the true triaxial tests of unsaturated loess are costly. The discrete element method (DEM), has been regarded as an efficient tool to correlate the macro and micro-mechanical performances for loess. Since it can provide microscopic responses of cemented assemblies under different stress paths.

This paper presents the results of numerical true triaxial and wetting tests into the influence of wetting and loading on the collapsible behavior of loess. The 3D DEM simulations were used to investigate the changes of axial strain and the relationship between void ratio and bond breakage with water content when structural loess is wetted and subjected to complex stress state by performing the quick wetting (wetting the sample to saturation in one step) and gradual wetting (wetting the sample to saturation in several stages).

2 THE NUMERICAL TEST ON UNSATURATED STRUCTURED LOESS

2.1 Contact model and parameter calibration

The 3D bond and contact model of unsaturated structural loess was adopted (Jiang et al., 2019). The van der Waals force was introduced in this model. It has been applied to the oedometer and wetting test on unsaturated loess (Li et al., 2018). Previous tests proved that this model can reproduce the mechanical properties of unsaturated loess well. The specific simulation process and the physical meaning of the micro parameters are detailed in Jiang et al. (2019). The parameters are shown in Table 1.

2.2 The preparation of DEM specimens

The curve of particle size distribution in this study was shown in Fig.1. The particle density was 2710 kg/m³; the median diameter was 2×10⁻⁵m. Samples were constrained by six frictionless walls.

The method of Multi-layer with Under-Compaction Method (UCM) (Jiang, et al., 2003) was used to prepare the DEM samples (Fig.2). And the effect of van der Waals force was introduced in the sample preparation process. The van der Waals force was defined as follows:

\[ F_v = \sigma_{\text{vdW}} d^2 \]

where \( d \) is the median particle size (\( d_{50} \)), and \( \sigma_{\text{vdW}} = 4 \) kPa, which is the van der Waals stress.

2.3 Simulation scheme

Firstly, the DEM sample was confined on different confining pressures, and then the upper and lower walls controlled by a servo control algorithm moved in opposite directions. In the shearing process, the automatic time step of the program was about 5×10⁻⁵s. The mean stress (\( p = (\sigma_1 + \sigma_2 + \sigma_3)/3 \)) and the principal stresses coefficient (\( b = (\sigma_3 - \sigma_2)/ (\sigma_1 - \sigma_3) \)) remained unchanged during the shearing process. The principal stresses are servo controlled by:

\[ \sigma_2 = \frac{(3-3b)p-(1-2b)\sigma_1}{2-b} \]

\[ \sigma_3 = \frac{3p-(1+b)\sigma_1}{2-b} \]

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the maximum, intermediate and minimum principal stresses respectively.

The wetting methods included quick wetting (QW) method and gradual wetting (GW) method. The quick wetting method is wetting the sample to saturation in one step, and then stabilizing the sample. The gradual wetting method is wetting the sample to saturation in
several stages. The sample is wetted to the next water content only when the deformation of the sample is stable. The GW method is wetting the sample to saturation in several stages, i.e., 7.1% → 9.8% → 11.5% → 13.8% → 16.0% → 18.5% → 21.0% → 23.0% → saturation (The water content of the saturated samples were calculated to be between 30% and 35% according to different working conditions). Wetting was carried out at different deviatoric stress levels ($\sigma_\text{d} = q / q_{\text{peak}}$, where $q$ is the deviatoric stress of the specimen, $q_{\text{peak}}$ is the peak deviatoric stress or that at 15% axial strain of the specimen). The stress state was maintained during wetting.

3 DEM SIMULATION RESULTS AND DISCUSSION

Fig.3 shows the variation of axial strain of structural loess samples with different confining pressures. It can be concluded that collapsing failure occurs when the deviatoric stress approaches or exceeds the peak shear strength of the saturated at the same stress state. Two wetting methods have little difference in the collapsible deformation. When wetting at low deviatoric stress level, the wetting deformation wetted by QW is slightly larger than that by GW, while at high deviatoric stress level, the collapsible deformation of the sample wetted by QW may be slightly less than that by GW. The axial strain of the stabilized samples wetted by two wetting methods are greater than that of the saturated one at the same stress state in the true triaxial tests.

Fig.4 shows the change of void ratio with water content during wetting. The results of the saturated structural loess in the same stress state was illustrated by "x" in the figure. During the GW process, the volumetric strain of the sample gradually increases with the increase of the water content (volume shrinkage). However, the sample volume may dilate due to the shear failure. Comparing the two wetting methods, the volumetric strain of the sample wetted by QW is slightly larger than that by GW. The volumetric strain for the specimen wetted by the two wetting methods has little difference with that of the saturated one at the same state, and there is no obvious pattern.

Fig.5 shows the variation of the bond breakage number with different water contents. The results of the samples of the saturated structural loess were denoted by "x" in the figure. During the GW process, there is a threshold water content (about 10%) beyond which bond failure occurs. The threshold water content at low confining pressure is significantly higher than that at high confining pressure, which indicates that the initial bond failure surface is related to water content and stress state. According to the comparison between the two wetting methods, the bond breakage number of the sample wetted by QW is slightly higher than that by GW. The bond breakage number of the specimen wetted by the two methods is slightly higher than that of the saturated one at the same stress state in the true triaxial tests.
CONCLUSIONS

The 3D contact model of structural loess was adopted by introducing the van der Waals force and the interparticle chemical cementation. A loose and homogeneous DEM sample was prepared by using UCM. The simulation of true triaxial and wetting tests using different wetting methods were carried out to study the change in axial strain after wetting, and illustrate the changes in void ratio and bond breakage number with varying water content. The main conclusions of the study are summarized as follows:

1. When wetting at low deviatoric stress level, the collapsible deformation of the sample wetted by QW is slightly larger than that by GW, while at the high deviatoric stress level, the collapsible deformation of the sample wetted by QW is slightly less than that by GW.

2. The volumetric strain of the sample dilates due to shearing. Comparing the two wetting methods, the volumetric strain of the sample wetted by QW is slightly larger than that by GW.

3. The initial bond failure surface is related to water content and stress state. The bond breakage number of the sample wetted by QW is slightly higher than that by GW. The bond breakage number of the specimen wetted by the two wetting methods are slightly higher than that of the corresponding saturated one at the same stress state.

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