Discrete element analysis of the deformation and failure characteristics of deposits during biaxial compression based on flexible boundary

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Abstract. Deposits is a kind of discontinuous and non-uniform material composed of soils and stones. Due to the effect of the internal meso-structure, its deformation and failure mechanism under external load is more complicated than the general soil. In this paper, the deformation and failure process of deposits and its shear band formation under biaxial compression were investigated by discrete element simulations based on flexible boundary, and the influence of confining pressure and the content and spatial distribution of its internal stones on the deformation and failure characteristics were analyzed. The simulation results show that the deformation and failure of deposit is a progressive failure process. The formation of its shear band starts to appear and gradually develop before peak stress during compression, and it penetrates at peak stress and gradually expands after peak stress. The deformation and failure process of deposits is not only affected by its internal stone content and spatial distribution, but also depends on the confining pressure. In general, the morphology of the shear band after failure shows an asymmetrically X-shaped arrangement because of the effect of stones.

1. Introduction

Deposits is a kind of undesirable geological body formed by Quaternary accumulation, which is characterized by the mixture of soil and stone. It is widely distributed in the mountains and valleys in the southwest area of China, and is also one of the main disaster-bearing bodies of geological disasters such as landslides and debris flows in this region[1-3]. It is of great engineering value to study deformation and failure mechanism of large-scale deposits for disaster control in southwest China.

Aiming at the deformation and failure mechanism of deposits, many scholars at home and abroad have carried out a large number of researches in this field, including experimental tests and numerical simulations[4-6]. For instance, Wang Y et al.[7] investigated the fracture mechanisms that govern the strength and deformation of SRM subjected to uniaxial compression loads by means of computed tomography (CT) techniques. Hai-Yang Zhang et al.[8] analyzed the interaction of the internal rock blocks and the evolution of the sample meso-structure in the loading process, based on X-ray computed tomography (CT) slices of samples taken during the triaxial tests. The current research results show that the deformation and failure process of deposits is extremely complicated, and the formation of its shear band is largely controlled by the internal meso-structure, and is significantly
affected by the characteristics of the internal meso-structure such as the content, spatial distribution and gradation of stone.

In this paper, from the viewpoint of meso-structure, the deformation and failure process of deposits and its shear band formation under biaxial compression were investigated by discrete element simulations based on flexible boundary, and the influence of confining pressure and the content and spatial distribution of its internal stones on the deformation and failure characteristics were analyzed. Research results have the important theoretical value for revealing the deformation and failure mechanism of deposits.

2. Establishment of discrete element model of deposits

2.1. Establishment of random mesoscopic structure model

Due to the great randomness of the meso-structure of deposits in nature, the common method used in the existing research is to establish the random meso-structure model of deposits. In this study, the irregularly convex and concave polygons are used to represent the stones in field and establish the random meso-structure model[9].

In order to study the influence of the content and spatial distribution of stones on the deformation and failure characteristics of deposits, the random meso-structure models with the stone contents of 30%, 45% and 60% were established respectively, as shown in figure 1. In addition, under the stone content of 45%, two more random meso-structure models were established respectively, in which the stones have the different spatial distribution, as shown in figure 2. The dimensions of all models are 5cm (Width)×10cm (Height). In the model, the size of a stone obeys normal distribution, and its probability density function can be expressed as follows:

\[
f(\lambda) = \frac{1}{\lambda \sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln \lambda - \mu)^2}{2\sigma^2}\right], \quad 0 < \lambda < \infty
\] (1)

Where, \(\lambda\) represents the size of a stone, which is referred as the maximum of the distance between any two vertices of an irregular polygon, and \(\mu\) and \(\sigma\) are respectively the mean and variance of stone size, whose values are respectively 1.28 and 0.23. The flatness of a stone is between [1.0, 3.0], which is defined as the ratio of the maximum to the minimum distance between any two vertices of an irregular polygon.

![Figure 1. Random meso-structure model of Deposits samples with different stone contents.](Image)

![Figure 2. Random meso-structure models of deposits samples with the same stone content but different spatial distributions.](Image)
In those simulations, each soil particle in deposits sample is represented by single ball, and each irregular stone is represented by a clump. A method of preparation of numerical samples based on the random meso-structure models is proposed for deposits in this work, as shown in figure 3. It includes two steps: a model of balls is generated to represent soil first, as shown in figure 3(a); then, the ball model is overlaid with the random meso-structure model, as shown in figure 3(b); after that, the balls covered by each stone are determined respectively, if their centres are located inside the boundary of the stone, as shown in figure 3(c); at last, the balls covered by each stone are clumped together into a clump, and other balls represent soil particles, as shown in figure 3(d).

![Figure 3](image)

**Figure 3.** The establishment processes of DEM model for deposits samples.

Based on the random meso-structure models shown in figure 1 and figure 2, the proposed method is used to generate their corresponding discrete element models, as shown in figure 4 and figure 5.

![Figure 4](image)

**Figure 4.** DEM models of deposits samples with different stone contents.

![Figure 5](image)

**Figure 5.** DEM models of deposits samples with the same stone content but different spatial distributions.

3. **Discrete element simulation of biaxial compression test based on flexible boundary**

3.1. *Model of biaxial compression based on flexible boundary*

In the conventional biaxial compression test, confining pressure is applied on the lateral rigid walls by servo mechanism, which limits the non-uniformly free deformation of the sample in lateral direction. In this study, the flexible membrane is used to simulate the loading of confining pressure in laboratory test.

Figure 6 shows the model of biaxial compression test based on flexible boundary. It is composed of the upper and lower rigid walls and left and right flexible membranes. The upper and lower rigid walls
are used as loading plates, whose normal velocity is fixed at 0.5mm/s in the test. Each of flexible membranes consists of a number of balls, and the contact bond model is used for those balls in order to ensure the transmission of force rather than torque between them, realizing the flexible loading of confining pressure. Meanwhile, in order to prevent the failure of the flexible membrane during the simulation, the bond strength between those balls is set to a large value.

In the numerical test, confining pressure is applied by the equivalent concentrated force exerted on each ball of flexible membranes, and the equivalent concentrated force is adjusted to maintain confining pressure constant during each step of cycles. Figure 7 shows a schematic diagram of the calculation of the equivalent concentrated force exerted on partial balls of flexible membrane. For any ball of flexible membranes, the equivalent concentrated force exerted on it can be calculated according to the following formula[10]:

$$
F_x = 0.5\left(\sum_{i=1}^{n} l_{ix} \cos \theta + \sum_{i=1}^{n} l_{iz} \cos \beta\right) \times \sigma_{\text{confining}}
$$

$$
F_y = 0.5\left(\sum_{i=1}^{n} l_{iy} \sin \theta + \sum_{i=1}^{n} l_{iz} \sin \beta\right) \times \sigma_{\text{confining}}
$$

(2)

![Figure 6. Model of biaxial compression test based on flexible boundary.](image)

![Figure 7. Schematic diagram of the calculation of equivalent concentration force.](image)

3.2. Contact model and parameters

In this study, the biaxial compression test is conducted by PFC 5.0[11], and the linear ebond model is used to account for contact interaction between soil and stone particles in the sample. The parameters of contact model for deposits used in the simulation are listed in table 1.

| Particles          | Density (kg/m³) | Contact stiffness (N/m) | Bond strength (N) | Frictional coefficient |
|--------------------|-----------------|-------------------------|-------------------|-----------------------|
|                    |                 | Normal | Tangent | Normal | Tangent |                   |
| Soil particle      | 2000            | 5.0e6  | 2.0e6   | 5.0e2  | 5.0e2   | 0.65               |
| Stone particle     | 2700            | 1.0e8  | 1.0e8   | -      | -       | 1.0                |
| Membrane particle  | 1000            | 5.0e5  | 5.0e5   | 1e300  | 1e300   | 0.0                |

![Table 1. The parameters of contact model for biaxial compression tests.](image)

4. Analysis of numerical simulation results

4.1. Stress-strain curves

Confining pressures ($\sigma_c$) in the biaxial compression tests are respectively 300kPa, 500kPa and 800kPa. Figure 8 shows the stress-strain curves of deposits samples with different stone contests and spatial distributions respectively under the confining pressure of 500kPa. It can be seen from figure 8(a) that
the stress-strain curves of deposits samples of different stone contents are different, and the higher the stone content is, the higher the peak strength for deposits samples is. It can be seen from figure 8(b) that the stress-strain curves of deposits samples with the same stone content are also different due to the different spatial distribution of stones in the samples. As can be seen from figure 8, compared with spatial distribution of stones in the samples, stone content has a more effect on their strengths.

4.2. Deformation and failure process

Taking the sample with stone content of 30% as an example, the deformation and failure process and the formation of shear band are analysed by comparison with displacement and rotation of particles in the sample under different axial strains.

Figure 9 shows the displacement and rotation nephogram of particles in the sample under different axial strains. As can be seen from figure 9, the particles in the deposits sample undergone non-uniform movement and localized rotation during the compression process, and the whole process of failure and formation of shear band is clearly reproduced by the particle rotation nephogram of the sample under different axial strains (See figure 9(b)). Moreover, it can be also found from figure 9 that the progressive deformation and failure is accompanied by shear band formation. Due to the effect of stones, the shear band is tortuous, and its formation appears an asymmetrically X-shaped arrangement in general.

In addition, it can be found from figure 8(a) and figure 9(b) that the formation of shear band starts to appear and gradually develop before peak stress during the compression process, and it penetrates at peak stress ($\varepsilon=3%$) and gradually expands after peak stress. As can be seen, the deformation and failure of deposits sample undergo a progressive failure process.
(a) particle displacement

![Particle displacement images](image)

(b) particle rotation

![Particle rotation images](image)

**Figure 9.** Displacement and rotation nephogram of deposits sample under different axial strains ($\sigma_c=500$ kPa).

4.3. *The influence of the content and spatial distribution of stones and confining pressures on deformation and failure characteristics*

Figure 10, figure 11 and figure 12 show the results of deposits samples under different confining pressures and the content and spatial distribution of stones, respectively. From figure 10, it can be found that the deformation and failure characteristics of deposits are different under different confining pressures, which reflects the non-uniform property of its composition. It can be also seen from figure 11 that the deformation and failure characteristics of deposits with different stone contents are significantly different under the same confining pressure, especially for the arrangement of shear bands. From figure 12, it can be found that due to different spatial distribution of stones, the deformation and failure characteristics of deposits are also significantly different even under the same confining pressure and stone content.

**Figure 10.** Simulation results of the same deposits sample under the different confining pressures ($C=30\%$).

**Figure 11.** Simulation results of deposits samples with different stone contents ($\sigma_c=500$ kPa).
Figure 12. Simulation results of deposits samples with the same stone content and different spatial distributions ($C=45\%$, $\sigma_c=500$ kPa).

In conclusion, the deformation and failure process of deposits is not only affected by the content and spatial distribution of its internal stones, but also depends on the confining pressure. Under the flexible loading of confining pressure, the morphology of its shear band after failure generally shows an asymmetrically X-shaped arrangement.

5. Conclusion

In this paper, the deformation and failure process and shear band formation of deposits was investigated by biaxial compression tests based on the flexible boundary, and the influence of confining pressure and meso-structural characteristics on the deformation and failure characteristics of deposits is analyzed. The following conclusions are drawn:

(1) The deformation and failure of deposits is a progressive failure process during the biaxial compression, and the formation of its shear band starts to appear and gradually develop before peak stress during the compression process, and it penetrates at peak stress and gradually expands after peak stress.

(2) The deformation and failure process of deposits is not only affected by the content and spatial distribution of its internal stones, but also depends on the confining pressure. Due to the effect of stones, the morphology of its shear band after failure generally shows an asymmetrically X-shaped arrangement.

Acknowledgments

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