Stability Analysis of Coal-Measure Soil Slope Based on Discrete Element Method

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Abstract. This paper uses the discrete element method to take the Pinglian high-speed coal-measure soil slope as the background, which uses PFC3D to calibrate the parameters, establishes the slope model, and analyzes the factors affecting the instability of the coal-measure soil slope from the granular meso-level. The results show that the discrete element method can be used to simulate the entire process of slope deformation and instability, and the sliding surface of the slope failure can be directly displayed through the displacement of the soil; the nature of the particles will affect the stability of the slope. The larger the particle size is, and the more irregular the composition of the soil particles are, the higher the safety factor of the slope is; the greater the slope is, the faster the safety factor decreases. When the slope is less than 1:0.75, the slope is relatively stable.

1. Introduction

As a kind of poor engineering soil, coal-measure soil is widespread in southwestern Jiangxi. Its carbon content is high, its appearance is gray-black, the soil structure is loose, it is easy to weather after excavation, and it is easy to swell and disintegrate when exposed to water. Some scholars have combined laboratory tests and numerical simulation tests to conduct research on the shear strength and the influence laws of coal-measure soil under different water content states, and the change law of coal-measure soil soil-water characteristic curve under dry and wet cycle conditions, and the slope seepage field under rainfall infiltration [1-3]. At present, there are few research results on coal-measure soil slopes, and the numerical simulation analysis is mainly based on finite element, and the analysis of the meso-breaking mechanism of coal-measure soil is less involved.

Discrete element method to simulate slope instability has the advantages of discontinuity and large deformation, which is gradually used in slope research. Wei et al. [4] used the particle flow method to analyze the movement characteristics of the landslide that occurred in Mabian County, Leshan City, Sichuan Province on May 5, 2018. Shi et al. [5] used PFC and FLAC software to establish a slope model to analyze the stability of the Zhenggang slope along the Lancang River. Hou et al. [6] used PFC2D to establish a slope model to simulate the high weathered, moderately weathered sandstone and mudstone rock layers of the slope sediments of the Ya’an- Kangding expressway, and analyzed the failure mode and mechanism of the slope particle system under the action of earthquake. This paper uses the discrete element method to calibrate the particle parameters using PFC software, establishes a slope model, changes the particle parameters, and analyzes the impact of particle size, particle bond strength, slope, and particle shape on the instability of coal-measure soil slopes from a meso-level perspective to understand the influencing factors of slope damage.
2. Parameter Calibration and Model Establishment

2.1. Calibration of Meso-Parameters of Coal Measure Soil

The test soil sample was taken from a coal-measure soil slope in the A1 section of the Pinglian Expressway. The coal-measure stratum in this area is widely distributed. We take the coal-measure soil from the slope of the site and perform it with unconsolidated and undrained triaxial compression tests under confining pressures of 0.1 GPa, 0.3 GPa, and 0.5 GPa to obtain the deviatoric stress-axial strain curve. In order to analyze the instability of coal-measure soil slopes well, the actual soil particle size is enlarged and concentrated, and the particle size is randomly distributed with equal probability between 0.05 m and 0.1 m.

By controlling the particle friction coefficient, bonding strength, particle stiffness, particle modulus, stiffness ratio under the confining pressure of 0.1 GPa, 0.3 GPa, 0.5 GPa, and after repeated trial calculations to get the deviatoric stress-axial strain curve of the numerical simulation approaching the indoor test. The obtained meso-calibration results are shown in table 1. The numerical simulation curve and the indoor test curve are shown in figure 1. It can be seen from the figure that the change trend and size of the simulation curve under the parameters in table 1 are closer to those in the indoor test, indicating that this parameter can be better used for simulate coal-measure soil analysis.

Table 1. Microscopic parameters of coal measure soil.

| Coefficient of friction | Particle size (m) | Normal/Tangential bond strength (N/m) | Porosity | Density (kg/m³) | Particle modulus |
|-------------------------|-------------------|---------------------------------------|----------|-----------------|-----------------|
| 0.5                     | 0.05–0.1 m        | 4.5×10⁴                              | 0.35     | 2400            | 3×10⁶           |

![Figure 1. Calibration of coal-measure soil particle parameters.](image)

2.2. Slope Model Establishment and Stability Judgment Method

Generating the wall by PFC3D and generating particles in the wall with the parameters in table 1. The size of the slope model is 5 m (length) × 3 m (width) × 2.5 m (height), and its slope is 1:1; the basic particles in the model are spherical particles to reduce the model for the calculation requirements, and the total number of particles generated in the model is 8978. The slope model is shown in figure 2. In order to facilitate the observation of the movement of particles in different positions, the particles in the slope are treated in layers. Generating particles are in the slope model. We remove the upper part and the wall on the slope after the particle calculation is stable, waiting for the particles to calculate and stabilize again, and we finally apply a load on the slope model.
A model is established by PFC to simulate the instability process of the slope. As shown in figure 3, as the external load is applied, the slope reaches a critical state and then becomes instability. The instability process can be expressed by particle displacement. Slope instability is a gradual process. At the initial stage, particle movement is mainly concentrated in the local area, and no obvious slope movement is observed; as the time increases, the movement of particles gradually extends to the depth of the slope, and the slope occurs obviously Sliding, the sliding surface is generated; after the particle movement of the slope body reaches equilibrium, the particles no longer move, and the slope becomes stable again. Using the discrete element method to analyze the slope instability process is similar to the actual slope instability, and the sliding surface can be clearly observed, which is closer to the reality than the finite element analysis of the slope instability.

At present, when analyzing slope instability through the discrete element method, the strength reduction method and the gravity increase method are mainly used to obtain the slope safety factor [7]. This paper uses the gravity increase method to solve the safety factor. The gravity increase method is the ratio of the gravity acceleration that reaches the critical state of instability to the inherent gravity acceleration of the object:

$$F_s = \frac{g'}{g}$$

Among them, $F_s$ is the safety factor, $g'$ is the critical acceleration of gravity, $g$ is the acceleration of gravity. This paper uses the gravity increase method to solve the safety factor.

3. Analysis of Numerical Simulation Results

3.1. The Influence of Particle Size on Slope Stability

The particle size of different soils is different. In the project, the soil is classified according to the particle size in order to understand the properties of various types of soil well. The mechanical properties of different types of soil are quite different, and the soil with better gradation often has better properties; in order to understand the influence of soil particle size on slope stability, the particle size distribution is changed when other parameters of the particle are the same. After adjusting the particle gravity acceleration, the safety factor is calculated as shown in table 2. As the particle size distribution increases, the number of particles generated in the slope decreases significantly, while the safety factor of the slope increases significantly, indicating that the particle size has a greater impact.
on the stability of the slope. The larger the particle size is, the more stable the slope is.

**Table 2.** Slope safety factor under different particle size.

| Particle size (m) | Number of particles generated | Safety factor |
|------------------|------------------------------|---------------|
| 0.05–0.07        | 19111                        | 2.04          |
| 0.07–0.09        | 8091                         | 2.86          |
| 0.09–0.11        | 4051                         | 3.98          |

3.2. The Influence of Slope on Slope Stability

Slope has an important influence on slope stability. In engineering, in order to make the slope safer, cutting slopes with some conditions is a common method. In the slope under the same conditions, the smaller the slope ratio is, the better its stability is. In order to analyze the influence of slope on its stability, the slope models of different slopes are established as shown in figure 4. The slope model is established according to the slope commonly used in the design process, which is closer to the reality; in the loading process, the particle of the parameters are kept consistent, and comparing the changes in the slope safety factor under different slopes.

![Figure 4. Slope models under different slopes.](image)

The safety factors calculated in different slopes are shown in table 3. As the slope ratio decreases, the slope becomes slower, the safety factor increases significantly, and the slope is more stable, which is consistent with the actual situation. It can be seen from the data that when the slope is large, the slope safety factor is very small, and it is likely to cause the slope to be unstable under the action of external factors; when the slope is slow, the slope is relatively stable; the slope is below 1: 0.75, the slope is relatively stable, so in the steep slope, the slope can be cut if possible, otherwise other protective treatments are required to ensure the safety of the slope.

**Table 3.** Slope safety factor under different slopes.

| Slope ratio | 1:0.5 | 1:0.75 | 1:1 | 1:1.25 | 1:1.5 |
|-------------|-------|--------|-----|--------|-------|
| Safety factor | 1.32  | 2.04   | 3.06| 3.82   | 5.61  |

3.3. Influence of Particle Shape on Slope Stability

In the actual environment, most of the soil particles present irregular shapes. In order to simplify the calculation and modeling process, the above-mentioned particle parameter calibration and other factors affecting slope stability are all modeled by spherical particles; many studies have found that the particle shape has a great influence on the force of soil. The shear strength of spherical particles is lower than non-spherical particles. Generate particle models of different shapes through PFC software programming as shown in figure 5.
Generating three kinds of particle slope models and calculating the safety factors of different particles as shown in table 4. The safety factor of cylindrical particles is the largest, followed by ellipsoidal particles, spherical particles are the smallest, and spherical particles have the most unstable slope. From the data point of view, different particle shapes have an impact on the slope stability under the same conditions; from the particle shape, there is mutual occlusion between irregular particles, and the cylindrical is better than the ellipsoidal, resulting in the increase of the soil between friction angle and the shear strength of the soil, and the slope is more stable.

| Particle shape | Spherical | Cylindrical | Ellipsoid |
|----------------|-----------|-------------|-----------|
| Safety factor  | 3.06      | 3.77        | 3.36      |

4. Conclusion
(1) Coal-measure soil slope instability is a gradual process. After reaching the critical state of instability, the surface soil particles move and gradually expand to the inside of the soil. The whole slope moves, and finally the slope stress reaches equilibrium. Finally the particles are stable again, forming an approximate circular arc sliding surface.

(2) The larger the particle size and the higher the safety factor of the slope is, the more stable the slope is; the more irregular the shape of the particles, the stronger the inter-particle occlusion and the larger the soil friction angle is, the more stable the slope is; The smaller the slope ratio, the slower the slope and the greater the safety factor of the slope is, the larger the increase and the slope ratio is less than 1:0.75, the slope is relatively stable.

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