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Numerical simulation study on macroscopic mechanical behaviors and micro-motion characteristics of gangues under triaxial compression

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ABSTRACT

This paper describes the numerical research that studied the macroscopic mechanical behavior and the microscopic particle movement of gangue with different gradation under different confining condition and loading rate. Two types of compression tests, confined compression tests and triaxial compression tests were simulated using the commercial numerical modeling software PFC^{3D}. Most of the gangues are irregular convex polyhedron in shape. When under compression, huge contact force can be generated between particles result in interlocking effect. In order to reproduce the interaction between gangues, this research used Clump Template tool in PFC^{3D} to generate clusters of particles to represent tailing particles. Following observations were made based on numerical modeling result: 1) reasonable particle gradation can significantly improve the anti-deformation capacity and decrease lateral stress coefficient of gangue. 2) In triaxial compression tests, the load bearing capacity of gangue increases with the increase of confining pressure. 3) Distribution of particles axial displacement showed 'horizontal layering' feature in confined compression tests, and showed 'concave layering' feature in triaxial compression tests. In triaxial compression tests, particles close to the mid-height and the sides of the sample have most significant lateral displacement, forming a triangular zone of significant lateral displacement. It is also found that smaller particles move more actively while the large particles have their own "movement inertia". 4) With the increase of confining pressure, the number of the contact force chains and the maximum contact force between particles within the sample increases gradually, also the interpenetration degree of the contact force chains gradually increased. Meanwhile, the number of contact force chains and the maximum contact force are comparatively higher by using confined compression condition than the confining pressure at the same stress state. 5) Large size gangue particles play the main role in anti-deformation and transfer of axial stress; the surface contact force of large particles is significantly greater than that of the small particles. 6) Faster loading rate may increase the measured load bearing capacity of the gangue sample under the same confining condition.

1. Introduction

As a green mining technology, solid backfill mining (SBM) is proposed to solve issues pertaining to coal reserves trapped under railways, buildings, water bodies and surface disposal of coal-mine wastes [1]. In addition to efficient disposal of coal-mine wastes (e.g. gangues, fly ash), additional benefits of SBM include reduced surface disposal of coal-mine wastes, increased resource recovery, and decreased influence of surface subsidence. Accordingly, SBM has been one of the pivotal technical approaches to realize the green mining [2]. In the SBM process, the backfill body, as the main part to support overlying strata, has efficiently changed the stress state of both coal and surrounding rocks. The mining pressure are sustained by the backfill body and surrounding rock mass together [3], therefore, the strata movement in SBM have changed fundamentally compared with the traditional method of caving mining and the control of strata movement directly depend on compaction properties of backfill materials [4]. Loose gangues are commonly used as the backfill materials and the deformation-resistant ability of loose gangue is critical to filling quality. Loose gangue is non-cohesive materials and its particles are generally of convex polyhedron shape. The contact between gangue particles can be categorized as angle to face contact and angle to angle contact [5–6]. It is important to study the compressive mechanical properties of gangue to master and improve its anti-deformation capacity and ensure the filling quality.

Up to date, researchers have carried out decent amount of studies on the mechanical behavior of non-cohesive granular material. Jiang et al.

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[7] conducted large-scale triaxial compression tests to the stress-strain behavior of coarse grained soil of different density under different confining pressure. Luo et al. [8] adopted PFC^{3D} to simulate triaxial compression tests on sand. They observed the development of shear bond and related curves. Bagherzadeh-Khalkhaili [9] studied the effects of maximum grain diameter on the strength of the coarse grained soil. Dang et al. [10] studied the influence of shear rate on the shear strength of sand under triaxial compression test. Huang [11] used gangue particles from Pingdingshan No.12 coal mine as experiment material and studied its time related compressive behavior. Despite many useful findings, most of abovementioned research programs are focused on the mechanical behavior of non-cohesion soil rather than gangue.

Qi et al. [12] pointed out that for granular soil, the composite of material, the alignment of grain particles and the contact force between particles (namely soil structure) are the critical factors that determine the macroscopic mechanical behavior of the soil. For gangue, the material composite and structure are likely to be significantly different from granular soil. Also, most of the concurrent research on gangue focuses on macroscopic compressive behavior of gangue under static axial loading and stiff lateral confinement. But under the actual engineering condition, the filling material cannot be in the absolute confining environment in the goaf. Under the overlying strata load, the side pressure of the filling material is maintained at a certain level due to the compression deformation of the gangue wall or the small coal pillar. In the actual situation, it's in a true triaxial compression state. There is limited understanding regarding microscopic movement characteristics of gangue particles and influence on macro-scopic mechanical behavior of gangue conglomerate. This research uses numeral simulation software PFC^{3D} to study the macroscopic mechanical behavior of gangue as well as the microscopic gangue particle movement characters under both confined compression and triaxial compression loading condition. The research results not only provide a theoretical basis for the deep understanding the compaction mechanics characteristic of loose gangue, but also have important significance to selection of the filling material for solid backfill coal mining and perfecting solid backfill coal mining theory.

2. PFC^{3D} and gangue clump generation

2.1. Introduction to PFC^{3D} simulation

PFC^{3D} is a commercial numerical modeling code developed by Itasca Consulting Group base on Distinct Element Method in Discontinuous Mechanics proposed by Cundall and Strack [13]. PFC^{3D} uses spherical particles or ellipsoid pebbles as distinct elements, and uses particles/pebbles or clusters of particles/pebbles to represent objects to be simulated. PFC^{3D} is able to simulate the interactions between large amounts of discrete objects, or simulate the large deformation and fracture process within an object. The software is capable of simulation of many microscopic characteristics that cannot be done using other numerical modeling software [14–15].

PFC^{3D} uses a time stepping algorithm. The Newton's law of motion and a force-displacement law was alternative used within a calculation cycle to calculate the movement of the particles and change of contacting forces during a tiny interval of time (a time step) [16]. Fig. 1 illustrate how the position of particles/walls and contacting forces updated during calculation cycles.

2.2. Generation of irregular gangue particles

2.2.1. Statistical analysis of shape of the gangue block

The filling gangue used in the fully mechanized solid backfilling coal mining is those treated by crushing and sieving, and the particle size is usually 0–70 mm. In this paper, ImageJ image processing software is used to carry out statistical analysis of the shape of gangue of different diameters used in solid filling mining. The detailed analysis procedure is as follows: ① use digital camera to capture high-definition digital images of randomly selected gangue blocks (shown in Fig. 2(a)); ② two value processing is performed on the imported digital image, using the ImageJ image processing software (shown in Fig. 2(b)); ③ the boundary contour of the gangue block is extracted using the Analyze particles function of ImageJ image processing software (shown in Fig. 2(c)).

The statistical analysis shows that the shape of the gangue block used in solid backfilling coal mining is mainly irregular convex polyhedron with edges and corners, and the long axis and short axis of the convex polyhedron are approximately the same.

2.2.2. Random generation of the gangue block model

The gangue particles are generally irregular convex polyhedron in shape and the length of long axis and short axis is approximation. The gangue particles interact with neighboring particles through point contact and interlocking force can be generated at contacting point when gangue takes external compressive load. The interlocking force can restrain slip and rotation of the gangue particles, and further influence macroscopic deformation characteristics of the gangue. In PFC^{3D}, if gangue particles were modeled as particles/pebbles or clusters of particles/pebbles, the surface of each discrete particles would be smooth, and the interlocking effect between the gangue particles would not be simulated.

Based on this, this paper uses the Clump model in PFC^{3D}5.0 software to simulate gangue block. The Clump model and boundary surface program by secondary development of this paper aims to provide a closed constrained space with a definite shape for block. By specifying the size of the constrained space (i.e. the size of the simulated gangue block), a certain number of pebbles are filled in the target space area by constantly adjusting the radius and position according to the BubblePack algorithm of the software, and a rigid aggregate is formed. Overlapping is allowed between the pebbles. The filling is completed when the volume that the pebble fills is very close to that of the boundary surface (the error is less than the set value). In the end, the exterior contour of the Clump rigid aggregate formed by the pebble combination is very similar to that of the boundary surface of the secondary development, which is a geometric block of irregular convex polyhedron. By leveraging the secondary development of the program, the Clump rigid aggregate formed by pebble combination can more realistically reflect the shape of the gangue, the contact of edge-angle and angle-angle and the interlocking effect between the gangue particles, which makes up for rounded surfaces with no edges and corners of the pebbles. The random formation process of irregular gangue block is shown in Fig. 3. The relative position of pebbles in the 'clump' is unchanged in the

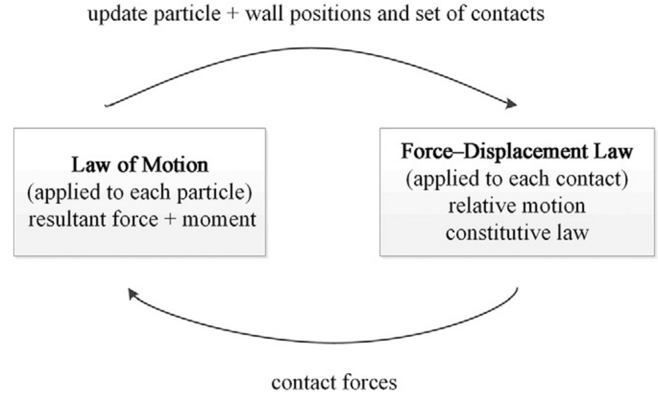

Fig. 1. Calculation cycle in PFC^{3D} [16].