International Journal of Mining Science and Technology 26 (2016) 309–317

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

A numerical study of macro-mesoscopic mechanical properties of gangue backfill under biaxial compression

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ARTICLE INFO

Article history:
Received 22 July 2015
Received in revised form 3 August 2015
Accepted 18 October 2015
Available online 20 January 2016

Keywords:
Gangue backfills
Particle flow
Biaxial compression
Shear band
Force chain

ABSTRACT

Based on the Particle Flow Code (PFC^{2D}) program, we set up gangue backfill models with different gangue contents and bond strength, and studied the stress–strain behaviours, the pattern of shear band and force chains, motion and fragmentation of particles under biaxial compression. The results show that when the bond strength or contents of gangue are high, the peak strength is high and the phenomena of post-peak softening and fluctuation are obvious. When gangue contents are low, the shape of the shear band is symmetrical and most strong force chains transfer in soil particles. With an increase in gangue content, the shape of the shear band becomes irregular and the majority of strong force chains turn to transfer in gangue particles gradually, most of which distribute along the axial direction. When the gangue content is higher than 50%, the interconnectivity of strong force chains decreases gradually; at the same time, the strong force chains become tilted and the stability of the system tends to decrease. With an increase in external loading, the coordination numbers of the system increase at first and then decrease and the main pattern of force chains changes into columnar from annular. However, after the forming of the advantageous shear band, the force chains external to the shear band maintain their columnar shape while the inner ones bend obviously. As a result, annular force chains form.

1. Introduction

Cut and fill mining is one of the main components in the technical system of green excavation of coal mines. Using cut and fill mining, the perturbation on the rock strata can be reduced and the movement of rock strata as well as ground settlement can be controlled. Therefore, it has become an effective approach to resolve the environmental issues of excavation of coal mines and issues of excavation of mines under buildings, railways, water bodies and mines above the artesian aquifer [1–6]. Under such an approach, the study of the mechanical characteristics of the backfill is one of the key techniques. Gangue backfill consists of gangue particles and soil particles. It is a typical non-continuum and the deformation of backfill, as well as the strength and stability of the structure, are controlled by the strength of particles, graduation of soil and gangue, form of skeleton element, type of connection between the particles and the arrangement of spatial position. The deformation and movement of the overlying rock strata are subsequently affected. Therefore, it is of engineering and theoretical significance to establish the relationship of the macroscopic and microscopic characteristics of the backfill and study the mechanical characteristics of gangue backfill from a mesoscopic perspective. At present, with the broadening of studies on the excavating techniques of backfill and their application, comprehensive studies on backfill materials have been conducted. The focus of established studies includes the compaction, fracturing and particle gradation as well as the creep characteristics of backfill materials such as coal gangue and loess having different moisture contents [7–14]. Studies have been mainly based on measurement and evaluation via macroscopic experiment.

At present, with the development of numerical methods and improvements in hardware, it is possible to evaluate the characteristics of particles at a mesoscopic level. The theory of the Particle Flow Code (PFC), based on the discrete element method, has been used to solve the issues of large deformation in solid mechanics and particle flow [15–22]. It is capable of addressing the difficulties of selecting the dimensions and controlling the loading of physical experimental instruments, and allows for convenient mesoscopic evaluation. A number of studies have been conducted on the mechanical properties of rock-soil materials using the above theory and substantial progress has been achieved [23–32]. Li and

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http://dx.doi.org/10.1016/j.ijmst.2015.12.018
2095-2686/

Zhuang et al. conducted numerical simulation using the PFC program and discussed the compaction characteristics of grouting backfill used in the collapsed region of strip mining [33–35]. At present, the study of the characteristics of gangue backfill using the particle flow method is rare. In this study, the particle flow PFC program was used to establish a gangue backfill model with different gangue contents and bond strength with consideration of particle fracturing. Biaxial compression numerical tests were conducted to evaluate the characteristics of backfill including stress and shear bands and particle fracturing. The pattern of relative movement of the particles of backfill was observed in real time from a mesoscopic perspective and the rotation, slipping, rearrangement and the form of force chains of particles under external load were studied.

2. Granular flow numerical model of gangue backfill under biaxial compression

2.1. Granular contact model

For all numerical samples in this study, the contact bond model was used between soil particles and the parallel bond model was used for gangue particles simulated by "clusters". The contact bond model allows balls in contact with each other to be bonded together, but bonding will only occur within a small range of the contact point, which is similar to a pair of springs with normal and shear stiffness acting at the contact point of the balls, where the springs have specified tensile and shear strength. Slipping is prevented as long as the contact bond exists. When there is no overlap of the balls, tensile normal contact force is allowed but cannot exceed the contact bond strength. The contact bond is defined by the normal contact bond strength F_c^n, and the shear contact bond strength F_c^s. When the magnitude of the normal tensile contact force is larger or equal to F_c^n, the bond breaks, and both the normal and shear contact forces are set to zero. When the magnitude of the shear contact force is larger or equal to F_c^s, the bond also breaks, but the contact forces are not varied. For parallel bond model, the two balls are treated as cylinders with a thickness of t. An elastic interaction is established between the two balls, but both forces and moments can be transmitted simultaneously between them, as shown in Fig. 1. The parallel bond can be viewed as a set of springs with constant normal and shear stiffness ($\bar{k}^n$ and $\bar{k}^s$) evenly distributed over the rectangular contact plane and centred at the contact point. In this case, relative movement at the contact point of the two bonding balls results in forces and moments which are related to the maximum normal and shear stresses of the material acting at the bond periphery. If any maximum stress exceeds its corresponding bond strength, the parallel bond breaks. In the parallel bond, the total force and moment on particle B are respectively $\overline{F}_i$ and $\overline{M}_3$, the normal and shear components of the force are respectively $\overline{F}_i^n$ and $\overline{F}_i^s$, and the increments at a time step Δt are, respectively, $\Delta\overline{F}_i^n$, $\Delta\overline{F}_i^s$ and $\Delta\overline{M}_3$, as calculated by:

$$\begin{aligned} &\overline{F}_i = \overline{F}_i^n + \overline{F}_i^s \\ &\Delta\overline{F}_i^n = (-\bar{k}^n A \Delta U^n) n_i \\ &\Delta\overline{F}_i^s = -\bar{k}^s A \Delta U_i^s \\ &\Delta\overline{M}_3 = -\bar{k}^n I \Delta\theta_3 \end{aligned} \quad (1)$$

where ΔU^n and $\Delta\theta_3$ denote the displacement and rotation, respectively. A and I are the area and moment of inertia of the bond cross-sectional which can be calculated as:

$$\begin{aligned} &A = 2\overline{R}t \\ &I = \frac{2}{3} t\overline{R}^3 \end{aligned} \quad (2)$$

in which $\overline{R}$ is the parallel bond radius. By setting $\overline{R}$, the bond can be limited within the range of $\overline{R}$ times of the radius of the smaller particle. t is the thickness of the particle. The new vectors of force and moment are superimposed on the original vectors. On the bonding plane, the maximum tensile and shear stress can be calculated by beam theory as follows:

$$\begin{aligned} &\sigma_{\max} = \frac{-\overline{F}^n}{A} + \frac{|\overline{M}_3|}{I}\overline{R} \\ &\tau_{\max} = \frac{|\overline{F}_i^s|}{A} \end{aligned} \quad (3)$$

If the maximum tensile stress exceeds the normal bond strength ($\sigma_{\max} \geqslant \bar{\sigma}_c$) or the maximum shear stress exceeds the shear bond strength ($\tau_{\max} \geqslant \bar{\tau}_c$), the bond breaks.

2.2. Numerical models

Gangue backfill consists of gangue particles with large diameters and soil particles with smaller diameters. In order to evaluate the mechanical characteristics of gangue backfill with different gangue contents, 10 types of samples with gangue contents ranged from 10% to 90% were established with a dimension of 0.3 m × 0.6 m, as shown in Table 1. As the grading of particle diameters for natural coal gangue is poor, the content of particles with a diameter larger than 5 mm is generally more than 60% and in some case, more than 80% [7]. The addition of soil particles with small particle diameter is able to improve the grading effectively. In this

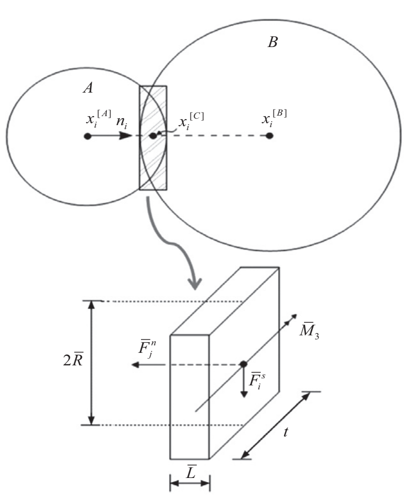

Fig. 1. Schematic diagram of parallel bond model.

Table 1
Gangue contents of gangue backfills samples.

Samples	Mass percentage of gangue particles (%)	Number of soil particles	Number of gangue particles	Total number of particles
1(a), 1(b)	10	7976	49	8025
2(a), 2(b)	20	7216	102	7318
3(a), 3(b)	30	6430	153	6583
4(a), 4(b)	40	5614	205	5819
5(a), 5(b)	50	4767	257	5024
6(a), 6(b)	60	3887	339	4226
7(a), 7(b)	70	2972	397	3369
8(a), 8(b)	80	2021	455	2476
9(a), 9(b)	90	1031	516	1547