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ORIGINAL ARTICLE

Coupled discrete element–finite difference method for analyzing subsidence control in fully mechanized solid backfilling mining

Xiaojun Zhu[1] · Guangli Guo[1] · Qi Fang[1]

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Abstract Fully mechanized solid backfilling mining is a "green mining" approach recently developed to control strata movement and reduce solid waste in China. In this mining technology, compaction characteristics of backfill materials and strata movement mechanism are the key factors to achieve effective ground control. In this study, the granular characteristic of backfill gauge and the continuous rock movement process are simulated by discrete element and finite difference methods, respectively. The dynamic process of coal extraction, strata movement, and backfill body compaction is simulated by a coupled method. The coupled method successfully simulates and assists in the analysis of the interaction among gangue backfill, overlying strata, and coal pillar, as well as the effect of the backfilling quality on subsidence control.

Keywords Coupled method · Numerical simulation · Fully mechanized solid backfilling mining · Subsidence control

Introduction

China is a major coal mining country, and its coal production has reached 3.87 billion tons in 2014 (Ministry of Land and Resources, P. R. China 2015), which was nearly half of the world's total coal production. Coal excavation produces a large void in the coal seam and disturbs the equilibrium of the original internal stress in the surrounding rock strata. This excavation leads to the bending and breaking of overburden strata and causes ground subsidence (Kratzsch 1983; Peng 2013). The latter is the most common type of disaster in mining areas and leads to damage of infrastructures, buildings, roads, and drainage systems (Marschalko et al. 2014; Xu et al. 2014). With increased mining in China, problems associated with ground subsidence have become progressively more serious over recent decades (Hu et al. 2004). Statistical data shows that the mining subsidence area in China is around 6×10^3 km^2, and mining subsidence area expands about 240 km^2 annually (Guo et al. 2011). Therefore, backfilling mining was developed to control ground subsidence and improve the eco-environment of the mining area. Along with the advances in backfilling technology over the recent years, solid backfilling in fully mechanized coal mining is proposed (Miao 2012). This backfilling technology, which is developed from the traditional solid backfilling mining, is one of the most widely used in China. To date, this technology has been applied in numerous mining areas, such as Xinwen coal mine, Huayuan coal mine, and Yangzhaung coal mine (Zhu et al. 2014; Miao and Zhang 2014). This technology uses solid waste materials, which are backfilled into goaf to replace the coal resource that was abstracted. Satisfactory backfilling quality is achieved by installing a ramming mechanism at the back of the hydraulic support to compact the backfill materials filled into the goaf (Zhang et al. 2011). Although the equipment and technology of fully mechanized solid backfilling mining have reached maturity (Zhang et al. 2015a, b), its strata movement laws and subsidence control mechanism require further studies. Aiming at this problem, several methods, such as field measurement, physical simulation, and numerical simulation, are used to study the strata

✉ Xiaojun Zhu
ying1989hun@126.com

[1] Key Laboratory for Land Environment and Disaster Monitoring of SBSM, China University of Mining and Technology, Xuzhou 221008, China

movement laws in backfilling mining (Zha 2008; Li et al. 2012; Huang et al. 2012). Among these methods, numerical simulation methods are the cheapest and easily repeatable.

Many scholars always simulate the process of strata movement and the characteristic of backfill material compression through a single numerical simulation method (discrete element method or continuum method). The discrete element method or continuum method has its own advantages and disadvantages while no one is really able to cover all facets of the rock mass behavior (Indraratna et al. 2015). In solid backfilling mining, the continuum method can easily deal with non-linear behavior and has high computation efficiency. In backfilling mining, the overlying strata can be regarded approximately as the continuum medium. The continuum method can be used to simulate the movement characteristics of the strata. But this method is difficult to simulate a lot of discontinuous behaviors. The discrete element method can easily treat the discontinuities existing in rock and simulate discontinuous brittle failure of the rock mass. This method can be used to simulate the backfilling body in solid backfilling mining, which is composed of discrete gangue, coal ash and loess. But the computational effort of distinct element method is considerable. Thus, an effective approach to solve the subsidence control problems of solid backfilling mining is by a coupled simulation method that links discrete and continuum medium (Felippa et al. 2001; Oñate and Rojek 2004; Cai et al. 2007; Zhou et al. 2010). This method combines the advantages or strengths of discrete and continuum method while avoiding many of their disadvantages. The strata movement mechanism and the compression characteristic of backfill material can be studied simultaneously through the coupled method.

In this paper, a coupled discrete–continuum method is applied to study the subsidence control of fully mechanized solid backfilling mining. The granular characteristic of backfill gauge and the continuity of rock movement process are simulated via discrete element method and finite difference method, respectively. The contact forces and displacements between continuum and discrete–continuum zones are determined through a contact law at the interface. Through this coupled discrete–continuum method, the interaction among backfilled gangue, roof, and coal pillar is studied. The influence of filling ratio, and porosity of the backfill materials on the characteristics of the backfill material compaction and overlying strata is also investigated.

Basic principle of the coupled discrete–continuum method

A brief introduction of FLAC and PFC

Fast Lagrangian analysis of continua (FLAC) is a finite difference program that can simulate linear or non-linear behaviors of soil, rock or other materials (Itasca 2005). The research object is represented by polygonal elements within a grid which is custom adjusted fit the arbitrary shape. The nodal velocity and displacement of the elements can be calculated according to a prescribed linear or non-linear stress/strain law in response to applied forces or boundary restraints.

Particle flow code (PFC) is a discrete element method program that simulates numerically the mechanical movement of an assembly of particles (Itasca 2004). The contact forces and the position of all particles can be calculated based on the law of motion and the predefined force–displacement law. A PFC model can be shaped to arbitrary shape by attaching hundreds of representative particles together, and then a complete set of micro-parameters is assigned to these particles to solve real problems containing complex deformation.

FLAC and PFC are both software systems of Itasca Inc. and have the same application programming interface (socket I/O interface), which indicates that computational data can be transmitted rapidly between FLAC and PFC on the same computer. Moreover, these two software systems are embed FISH language that enables the user to define new variables and functions. Thus, the data transmission between codes can be achieved by some FISH function calls.

Implementation of coupled discrete–continuum method

A number of similar material and numerical simulation tests show that the process of overlying strata movement is gentle and slow in fully mechanized solid backfilling mining, and no apparent caving zone develops in the overlying strata field (Guo et al. 2009). Thus, the movement of overlying strata can be simulated through finite difference method by using FLAC. The backfill materials are modeled with PFC to consider the discreteness of the complex nonlinear characteristics of backfill materials. The interaction between FLAC and PFC is determined through a contact law that allows PFC to transfer forces and displacements to FLAC and vice versa.

The coupled discrete element–finite difference method to simulate solid backfilling mining is implemented by the following steps:

1. A continuum mesh is initially created for the FLAC to model the rock strata and coal seam with a predetermined geometry and boundary conditions. The FLAC model is cycled to reach initial equilibrium under the action of self-gravity. The coal seam of a certain size is then mined.
2. PFC model assembly is generated with the input micromechanical parameters of backfill materials,

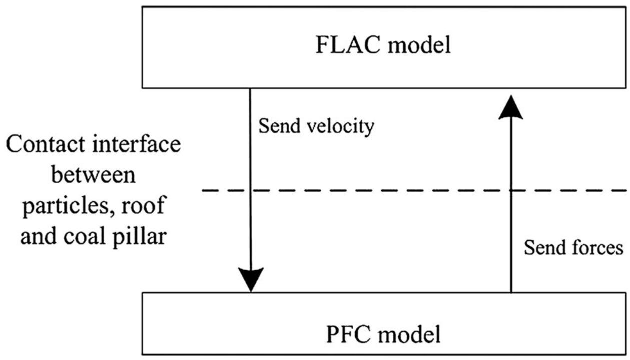

Fig. 1 The data transfer process in the coupled discrete–continuum method

where its size is the same with the excavation regions in FLAC.

3. FLAC model is running as the server, and a communication channel is opened via socket I/O interface for connecting with PFC. PFC particles should be slaved to FLAC element movement. Thus, the communication channel of velocities and forces between the two codes is developed.
4. The coupled model is then run with FLAC model while providing the velocities to the PFC model, and the PFC model sends forces to the FLAC model through the communication channel. In every time step, the two models send and receive velocities and forces from each other according to the contact law between a discrete particle and a continuum element. The data transfer process in the coupled discrete–continuum method is shown in Fig. 1. These iterations in both codes must be synchronized, which is achieved by running FLAC in static mode and PFC2D with differential density scaling (set dt = dscale).
5. In this way, the calculation in one-time step for the coupling between FLAC and PFC is completed. Subsequently, Step (4) is performed again, and the coupling calculation in the succeeding time step begins. The iteration step is continued until a balance which is reached for the model.

The special codes, written in the FISH language, are developed by the authors to implement an exchange of velocity and force at the interface between FLAC and PFC.

Contact law for coupling between a discrete particle and a continuum element

A contact law between a discrete particle and a continuum element has been presented in the FLAC manual (Itasca 2005). In this paper, the law is applied to exchange of velocity and force between the backfill body and the overlying strata in each iteration time step. The diagram of the contact between a particle and a continuum element is shown in Fig. 2. The particles do not come into direct contact with the nodes of continuum elements. Therefore, the velocity of the particle is obtained from the interpolation of nodal velocities of the continuum elements.

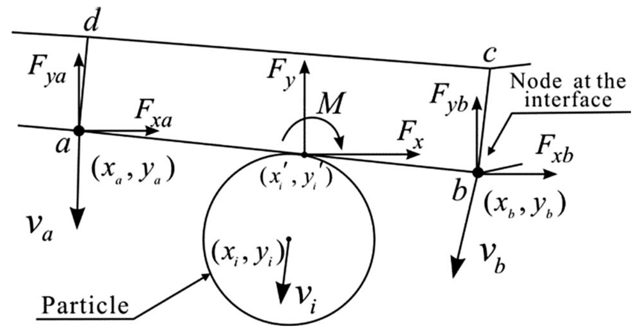

Fig. 2 Schematic of the contact between a particle and a continuum element

When contact between the particles and elements is formed, it can be described by the contact point (x_i', y_i') between a particle (x_i, y_i) and a continuum element (a–b–c–d) lying on an interface (a–b). Two nodal coordinates of the interface are (x_a, y_a) and (x_b, y_b), and their velocities are v_a and v_b, respectively. The velocity of the particle v_i can be determined by interpolating into the nodal velocities of the interface, and can be expressed as

$$v_i = v_a + \xi(v_b - v_a) \quad (1)$$

where ξ is the interpolation function of the velocity: $\xi = \sqrt{(x_i - x_a)^2 + (y_i - y_a)^2} / \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2}$.

The interface elements only receive applied forces from discrete particles at their nodes. Therefore, the contact forces and moment from the particles need to be converted to the nodal forces in the element. The force transmitted from the particle to the interface and the moment are $F_x F_y$ and M, respectively. The equivalent force vector transmitted from the particle to the two nodes on the interface are (F_{xa}, F_{ya}) and (F_{xb}, F_{yb}), respectively. The nodal force vector of the element can be determined by:

$$F_{xa} = \gamma \cdot F_x \quad \text{and} \quad F_{ya} = \gamma \cdot F_y \quad (2)$$

$$F_{xb} = (1 - \gamma) \cdot F_x \quad \text{and} \quad F_{yb} = (1 - \gamma) \cdot F_y \quad (3)$$

where γ is the interpolation parameter for the contact force: $\gamma = \frac{M - F_y \cdot (x_b - x_i) + F_x \cdot (y_b - y_i)}{F_y \cdot (x_a - x_b) - F_x \cdot (y_a - y_b)}$

Validation of the coupled model of solid backfilling mining

FLAC numerical model description

The simulation model of the backfilling working face in Yangzhuang coal mine is developed to validate the feasibility of the coupled model of solid backfilling mining. The Yangzhuang coal mine is located in Huaibei City, Anhui Province, China. A winery is located above this mining area and numerous brick houses. The working face is mined using the fully mechanized gangue backfilling mining to increase recovery rate, reduce the amount of solid waste, and protect existing ground structures. The working face extracts coal from No. 6 coal seam, with an average thickness of 2.7 m, an average depth of 405 m, an advancing length of 320 m and an incline width of 115 m. The extraction was carried out from October 2012 to December 2013. To guarantee filling quality, the average pressure of the ramming structure on the backfilling materials is 2 MPa to achieve a satisfactory degree of compaction. 42 observation points on the six buildings were observed in December 2014 and 3 observation points on the load above the III644 backfilling working face were observed in June 2014 in order to obtain the surface subsidence of solid backfilling mining. The layout of observation points above the solid backfilling working face is shown in Fig. 3. The subsidence values of the observation points were measured by fourth-order levelling survey (He and Yang 1991; State Bureau of Coal Industry 2000).

FLAC model and PFC model are modelled based on the strata structure. The graphic log of the strata structure is shown in Fig. 4. The schematic of the coupled numerical model is shown in Fig. 5. The coal seam is excavated and backfilled by steps. The left and right boundaries are fixed in horizontal direction, whereas the bottom boundary is fixed in both horizontal and vertical directions. Mohr–Coulomb model is adopted for the overburden strata. The mechanical parameters of the strata are calibrated using the laboratory test parameters of coal rocks and the in situ monitoring values of ground subsidence during backfilling mining. The strain-softening model is used for coal seam (Esterhuizen et al. 2010; Shabanimashcool and Li 2012; Li et al. 2015). The calibration mechanical parameters of the rock strata and coal are shown in Tables 1 and 2.

PFC numerical model description

The material behavior of the PFC model originates from the microscopic parameters of the particles that make up the material. However, the micromechanical parameters cannot be obtained directly from measurements on laboratory samples. The relevant behavior of the material is simulated by initially determining the appropriate microscale properties by a calibration process (Poulsen and Adhikary 2013).

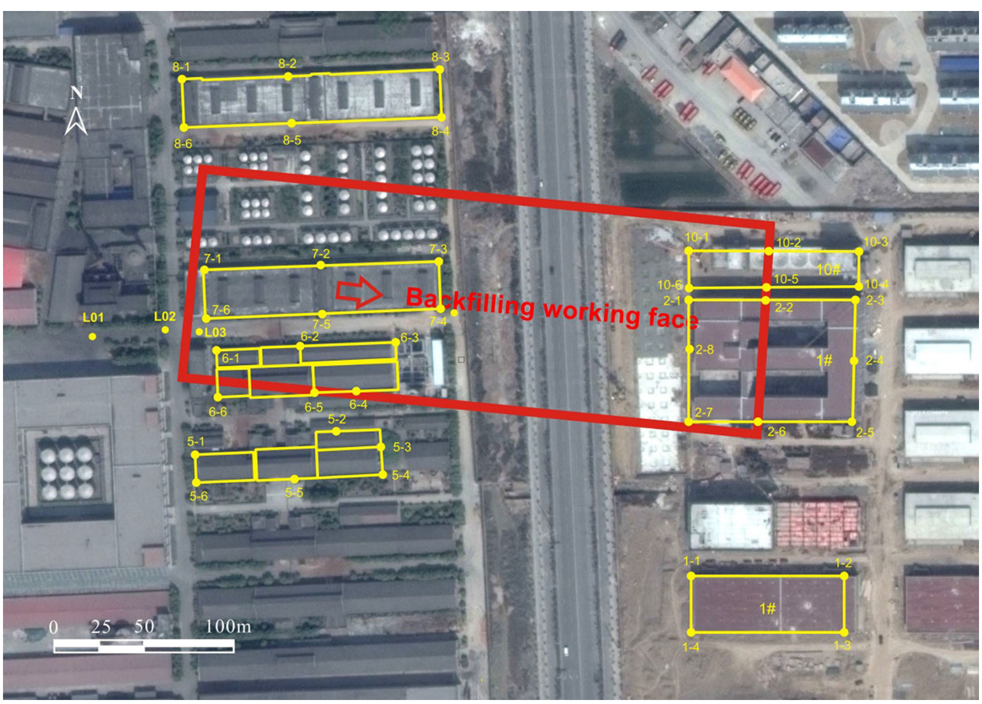

Fig. 3 The layout of observation points above III644 solid backfilling working face

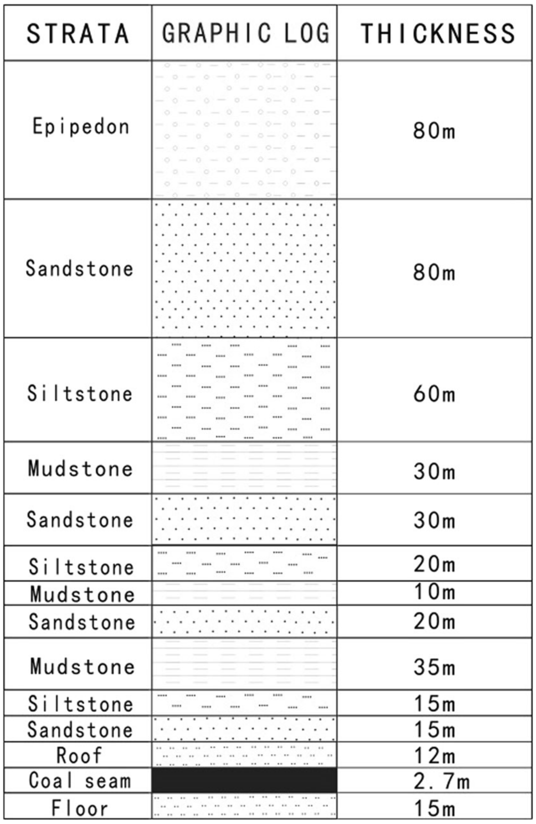

Fig. 4 The graphic log of the strata structure

Cylinder compression test

Cylinder compression test is performed to obtain the compressive deformation characteristics of the gangue backfill materials by using a microcomputer-controlled electronic universal tester YAW-3000 to calibrate the micromechanical parameters of backfill materials. The compression mold is a cylinder made of #45 steel with an inner diameter of 100 mm and a height of 280 mm (Fig. 7). The gangue sample used is obtained from the gangue backfill materials of backfilling working face in Yangzhuang Coal Mine. The size distribution of gangue particle is statistically analyzed prior to the experiments (Fig. 6). The stress–axial strain curve of gangue in the compression experiment is plotted.

Calibration of the microscopic parameters of PFC model

The simulation specimen is rectangular in shape with the same dimensions as those used in laboratory compression tests, with height of 280 mm and width of 100 mm (Fig. 8). The particle size distribution in the specimen is generated according to the actual size distribution of gangue. For compression test, the top and bottom walls serve as loading platens, and two side walls are fixed. The specimen is loaded by moving the top and bottom walls, and the stress–axial strain relationship of the simulation specimen is obtained. By comparing the stress–strain curve from numerical simulation with that obtained by laboratory cylinder compression test (Fig. 9), the micromechanical parameters, such as particle and bond stiffness, particle friction coefficients, and bond strengths, are constantly adjusted. Finally, a reasonable agreement between the simulation and measurement is achieved, and an appropriate set of micromechanical parameters is adopted for gangue particles. Based on the calibration, the micromechanical parameters are selected for the gangue backfill materials Table 3.

After the initial FLAC model is conducted and the microscopic parameters of the gangue backfill materials are calibrated, the coupled discrete element–finite difference method is implemented to simulate backfilling mining. The coal seam in the FLAC model is mined for a certain distance and the PFC model of the backfill materials with the same dimensions is generated. Subsequently, a communication channel is built between FLAC and PFC, and data exchange is performed on the contact interface. After completing the iteration process of coupled simulation method, the deformation of rock strata and the compaction characteristics of the backfill materials are obtained and analyzed.

Results

Figure 10 shows the roof subsidence curves of the coupled model. After the coal seam in the FLAC model is mined, the roof is no longer supported by the coal seam. The roof begins to subside continuously under the load of the overlying strata. Finally, the maximum roof subsidence is only 0.38 m. This roof subsidence is reduced by the force constantly transmitted from the backfilling particles in the PFC model.

Figure 11 shows the force chain between gangue particles at different distances from the face, and this figure only plots the force chain of half backfilling working face because of the symmetry. The particles are mutually contact and produce contact force under the force from the roof and coal pillar. The force chain of particle system is a means of force transmission and it may fracture and reconstruct under the influence of external load. The thickness of the force chain is directly proportional to the magnitude of contact force. Figure 11 shows that the adjacent particles form force chains of varying magnitudes under the action of roof, and these particles interconnect to create a network. The network ran through the gangue backfill materials from the roof to the floor. The contact forces show a non-uniform distribution in the backfilling working face. The width of the network between the

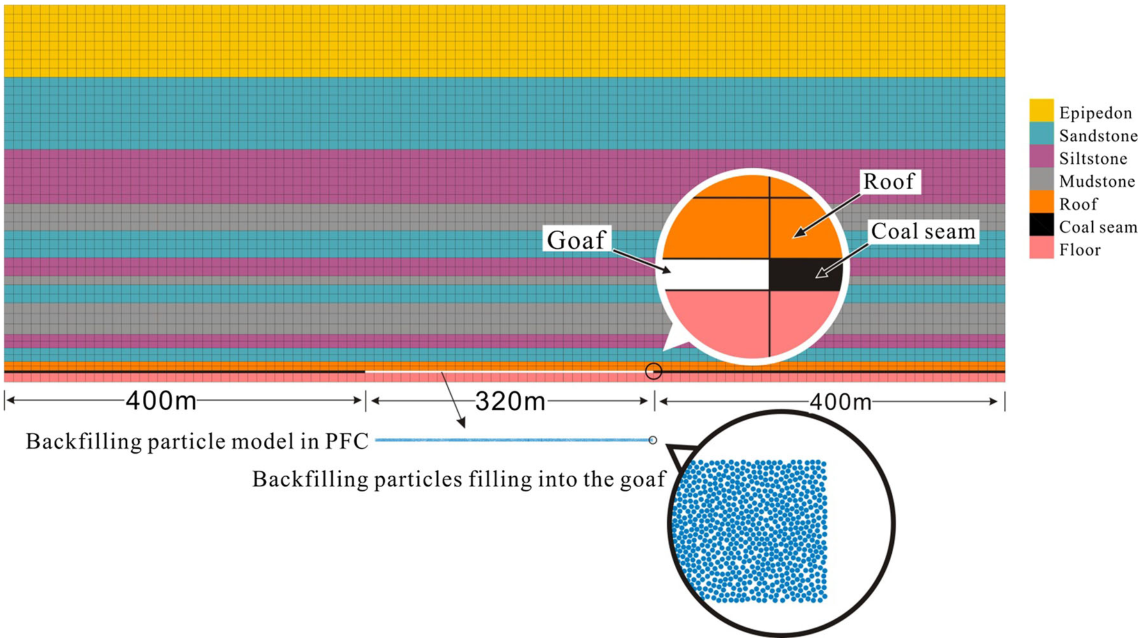

Fig. 5 Coupled discrete element–finite difference model of solid backfilling mining

Table 1 Mechanical parameters of the rock strata and coal

Strata type	Density (kg/m^3)	Modulus of elasticity (MPa)	Poisson's ratio	Cohesion (MPa)	Internal friction angle (°)	Tensile strength (MPa)
Epipedon	2000	30	0.32	0.5	24	0.05
Sandstone	2800	2080	0.2	6.4	49	1.5
Siltstone	2140	1280	0.25	5.2	37	1.7
Mudstone	2340	1020	0.3	4.8	29	0.7
Coal	1400	950	0.26	2.4	25	0.15

Table 2 Parameters of strain softening model of coal pillar

Strain (m/m)	Cohesion (MPa)	Strain (m/m)	Cohesion (MPa)	Strain (m/m)	Cohesion (MPa)
0	2.4	0.01	0.55	1.00	0.55

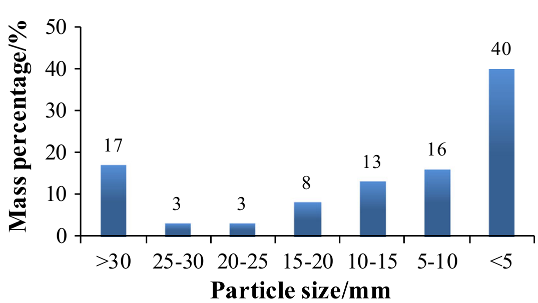

Fig. 6 Size distribution of the backfill materials

particles in the middle of the backfilling working face is larger, while those between the particles near the open-off cut are smaller. The porosity of gangue particles decreases from 0.3 to 0.18–0.29, which is affected by the load of the overlying strata. The porosity also shows a non-uniform distribution as shown in Fig. 12. The porosity is lower along the coal pillar than at the center. This indicates that the interaction between backfill materials and roof is different in varied regions.

Surface subsidence due to mining actually is a three-dimensional problem. But the coupled model in this paper is a two-dimensional model and the simulated surface subsidence curves are equivalent to the surface subsidence curves on the main section of the actual backfilling mining. So, some actual monitor points near the main section are chosen and their subsidence values are compared with the results of the coupled model.

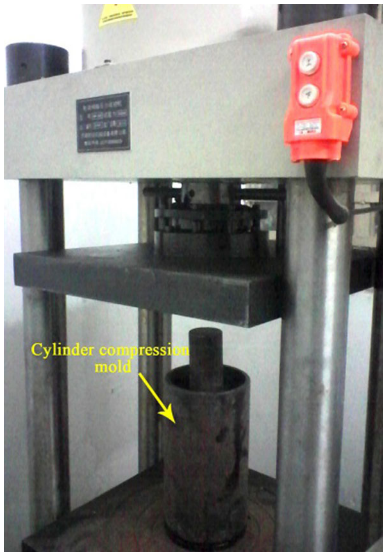

Fig. 7 Cylinder compression mold for mechanical experiment

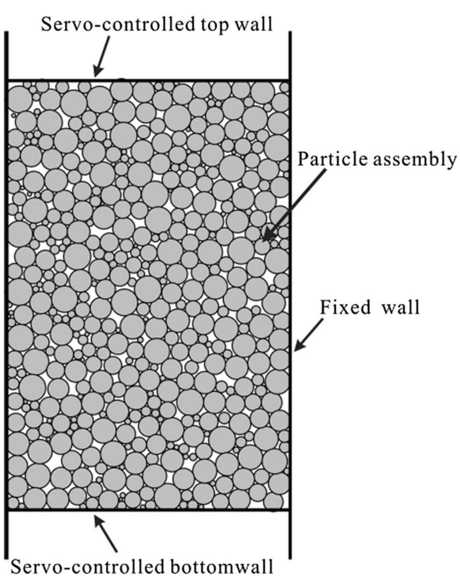

Fig. 8 Particle model in PFC

The ground maximum subsidence is located at the center of the backfilling working face. The subsidence gradually decreases from this point to the margin of the basins, which conforms to the characteristics of the ground subsidence in backfilling mining. As it can be seen from the Fig. 13, the surface subsidence values of monitor points basically coincide with the simulation results.

The simulation results indicated that the surface subsidence and the compression characteristics of simulated discrete gangue particles are close to the actual situation in solid backfilling mining considering the interface contact among gangue particles, roof, and coal pillar. Analyzing the mining

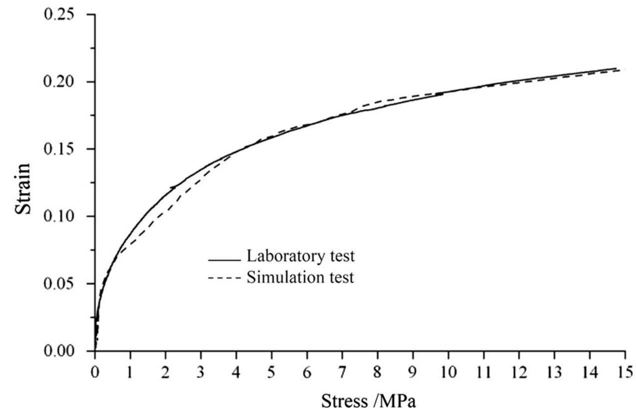

Fig. 9 Comparison of calibration stress–strain curve and test stress–strain curve

Table 3 Calibrated microscopic parameters of gangue particles

Parameter	Value	Unit	Note
ρ	2660	kg/m^3	Particle density
n	0.30		Porosity of the backfill materials
E_c	2	GPa	Particle–particle contact modulus
k_n/k_s	1		Particle stiffness ratio
μ	0.2		Particle friction coefficient
σ_c	0.1	MPa	Contact-bond normal strength
τ_c	0.1	MPa	Contact-bond shear strength

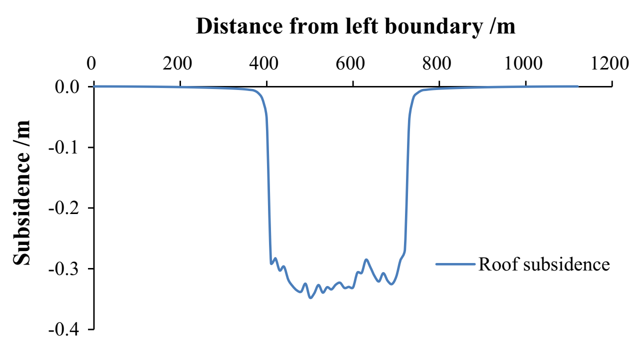

Fig. 10 Subsidence curves of roof

subsidence control of backfilling mining via the coupled discrete element–finite difference method is feasible.

When FLAC is used to simulate the solid backfilling mining, continuous elements are generally adopted to simulate the backfill body. Xu and Yao used the continuum element to simulate the strata and backfill materials by finite difference method, and simulated different compression ratios of backfill materials by change the elastic modulus of the continuum elements (Xu et al. 2011; Yao 2012). But, the coupled model which adopts discrete

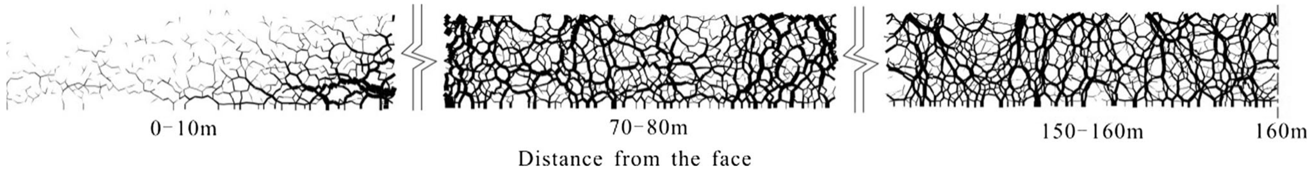

Fig. 11 Force chain of gangue particles in different regions of half backfilling working face

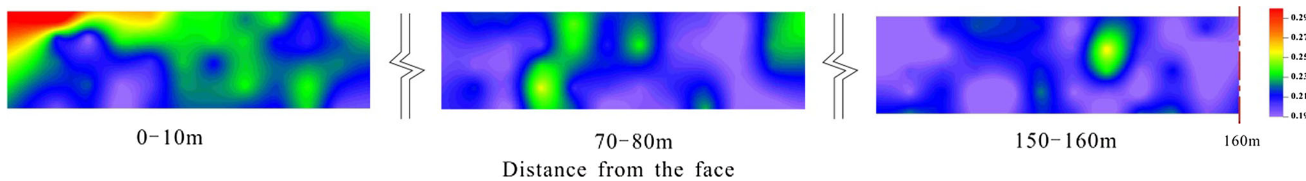

Fig. 12 Porosity nephogram of gangue particles in different regions of half backfilling working face

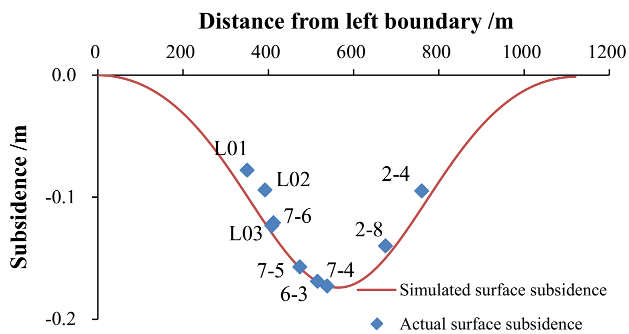

Fig. 13 A comparison between simulated and actual surface subsidence

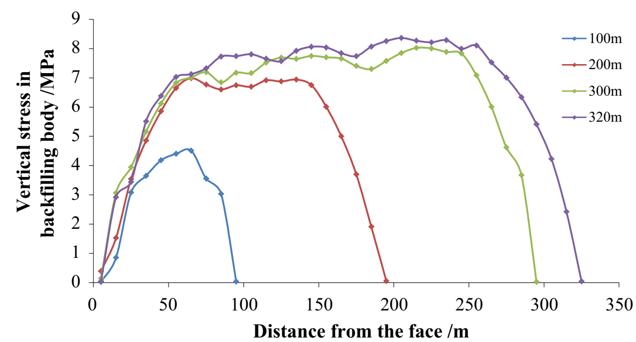

Fig. 14 Internal stress distribution of gangue backfill materials

particles to simulate the solid backfill body can simulate the effects of different porosity and particle size and other factors on surface subsidence in solid backfilling mining. The results in the coupled model are more realistic than that in the FLAC model. When PFC is used to simulate the solid backfilling mining, although backfill body is modelled by a small amount of the particles, but the overburden strata are modelled by a lot of particles. The computational efficiency of the PFC model is very low. The coupled model adopts a small amount of the continuous elements to simulate overburden strata, which greatly reduces the computation burden.

Discussion

Analysis of the interaction between the backfill materials and overlying strata

By the coupled discrete element–finite difference method, the interaction among the gangue backfill materials, rock strata, and coal pillar in solid backfilling mining is analyzed.

In the particle flow model, the stress as continuous variables between any two particles does not exist because the medium is discontinuous; thus, the stress within the particles cannot be obtained directly to study the stress distribution of backfill materials. A series of measurement circles is set from left to right at an interval of 10 m inside the backfill materials by an averaging procedure to compute the average stress. The stress distribution inside the backfill materials is measured as the backfilling working face advances. The stress inside the backfill materials fluctuates considerably because of the discreteness of gangue particles. The stress curve is smoothed to analyze the stress distribution characteristic. Figure 14 shows the curves of stress distribution inside the backfill materials as the working face advances for different distances.

The maximum internal stress of backfill materials is only 4.2 MPa when the face advances 100 m (Fig. 14). When the advancing distance of the working face is small, the backfill materials are not in full contact with the roof. Thereby, the compression ratio and internal stress of backfill materials are low. As the face advances, the backfill materials come in contact with the roof gradually and compact under overlying pressure. Thus, the internal stress of backfill materials increases correspondingly. After the face advances about 200 m, the backfill materials are compacted, and the maximum internal stresses increases by

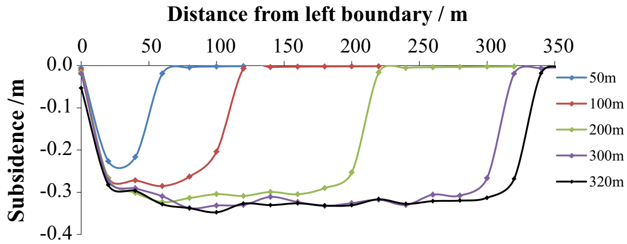

Fig. 15 Curves of roof subsidence as the face advances

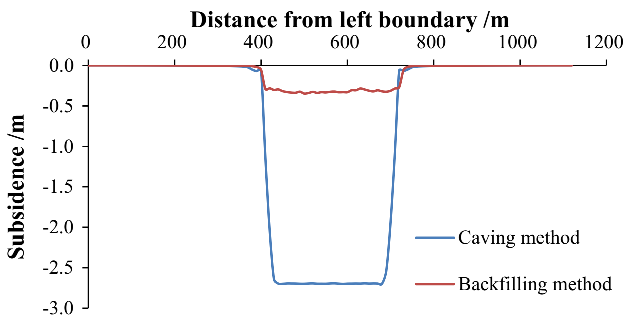

Fig. 16 Comparison of the roof subsidence curves in caving and backfilling methods

a lower margin. The maximum stress inside the backfill materials reaches 8.4 MPa after the working face advances 320 m.

Meanwhile, the roof subsidence curves gradually increase as the face advances because of the compression of backfill materials (Fig. 15). After the backfill materials are compacted, the maximum roof subsidence remains basically unchanged.

A model of caving method without gangue filling into the goaf is developed to analyze the effect of the support provided by backfill materials to the overlying strata. Figures 16 and 17 show a comparison of roof subsidence curves and the ground in caving mining and solid backfilling mining, respectively. After mining, the roof is broken into the goaf in caving mining. The roof subsidence value is 2.7 m, which is equivalent to the mining height, and the maximum ground subsidence is 0.56 m. In backfilling mining, the maximum roof subsidence is about 0.32 m, which is 0.12 times of the mining thickness. The maximum ground subsidence is 0.17 m, and the ground subsidence is reduced by 70 %. The failure height of overlying strata in caving mining is 32 m which is observed from plastic yielding zone of the FLAC model, whereas that in backfilling mining is 17 m, which is only 0.53 times that in caving mining.

The free space in goaf after coal mining is the main cause of the movement and failure of overlying strata. This problem is solved by transporting gangue backfill materials into the goaf to occupy the subsidence space of the

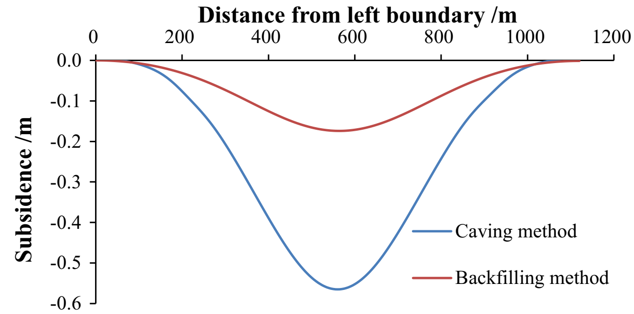

Fig. 17 Comparison of the ground subsidence curves in caving and backfilling methods

overlying strata via the conveying equipment and substituting these materials for the original coal seam to support the overlying strata. With the roof bending deformation, the backfilled gangue is gradually compacted and bears more load from the overlying strata. After the backfill materials are completely compacted, a stress balance is achieved between the roof and the gangue, and the roof stops subsidence. Therefore, the failure height and subsidence of overlying strata are both reduced. The goals of controlling the displacement of overlying strata and preventing ground subsidence disaster are satisfied in fully mechanized solid backfilling mining.

Analysis of the interaction between the backfill materials and coal pillar

Effect of the backfill materials on coal pillar

The model mesh of the coal pillar and the roof is segmented based on the original model to improve analytical precision. Figure 18 shows that the abutment pressure distribution of coal pillar in the two different mining methods is similar. However, the peak abutment pressure in backfilling mining is smaller than that in caving mining under the same geological conditions. The peak abutment

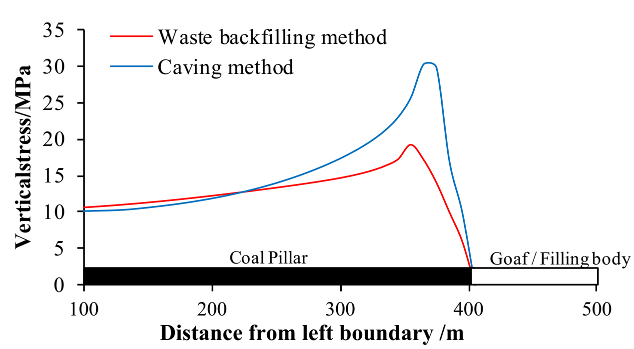

Fig. 18 Abutment pressure distribution of coal pillar in caving and backfilling methods

pressure in caving method is 30.2 MPa and that in backfilling mining is 19.2 MPa. Compared with caving mining, the load originally acting on the coal pillar is partially shared by the backfill materials in backfilling mining. Thus, the backfill materials reduce the abutment pressure in coal pillar in vertical direction.

The yielding zone widths of coal pillar in caving and backfilling mining methods are 12 and 3 m, respectively. In the horizontal direction, the backfill materials reinforce the coal pillar laterally. When coal is excavated, the coal pillars are no longer laterally supported on the side in caving mining, and the triaxial stress state in the coal pillars transform into the biaxial stress state. The coal pillars experience a considerable amount of deformation under overburden pressure and even undergo failure. When the backfill materials are placed around the coal pillar, the coal pillar, which is in the triaxial state, is supported by lateral confinement pressure. The additional vertical confinement of the fill increases the passive lateral pressure as the face advances. The backfilled pillar differs from the unsupported pillar and has a much higher resistance to compressive stresses. The strength of coal pillar subjected to a confining pressure can be determined from Mohr–Coulomb failure criterion (Wu et al. 1994):

$$\sigma_1 = \frac{1 + \sin\varphi}{1 - \sin\varphi}\sigma_3 + \frac{2c\cos\varphi}{1 - \sin\varphi} \tag{4}$$

where c is the cohesion of coal, φ is the internal friction angle of coal, σ_1 is the confining pressure on coal pillar, and σ_3 is the ultimate compressive strength of coal pillar. Smaller lateral stress σ_3 indicates lower compressive strength of the coal pillar. The compressive strength of the coal pillar is worst when $\sigma_3 = 0$. The backfill materials help provide lateral support to coal pillar, which enhances the compressive strength of the coal pillar and further reduces the collapse and yielding width of the coal pillar.

Effect of coal pillar on the backfill materials

Vertically, coal pillar helps reduce the internal stress of the backfill materials near the coal pillar. Figure 14 shows that the internal stresses of the backfill materials are unevenly distributed and form an arch shape. The stresses are lower along the coal pillar than those at the center. The reason for these low stresses is that the load of overlying strata near the coal wall is borne partly by the coal pillar. Therefore, the compaction degree and internal stresses of the backfill materials near the coal pillar are reduced.

In summary, the coal pillar and the backfill materials constitute a synergistic supporting system as they jointly support the load of the overlying strata in vertical direction. Given the backfill support, the abutment pressure of coal pillar in backfilling mining is smaller than that in caving mining. Meanwhile, the internal stresses of the backfill materials show an "arch-shaped" distribution, which is affected by the sides of the coal pillars. In the horizontal direction, the increase in coal pillar strength is due to the lateral confinement provided by the backfill materials.

Effect of the backfilling quality on subsidence control

Numerical simulation results in the previous section show that fully mechanized solid backfilling mining can control ground subsidence effectively. Many factors affect the subsidence control of solid backfilling mining, which is not only influenced by the geological mining conditions and filling technology but also by the mechanical characteristics of the backfill materials that fill into the goaf and quality of the backfilling. In given circumstances of geological mining conditions and the mechanical properties of the backfill materials, the backfilling quality can be optimized to reduce ground subsidence further. Particle flow model can simulate properly different backfilling quality. Thus, coupled models are developed to simulate the strata movement of backfilling mining by utilizing the different mechanical properties of backfill materials in this section. (1) Filling ratio is the ratio of volume of backfill materials filled into the goaf to the volume of the goaf. It is a technical measurement indicator to evaluate the goaf backfilling effectiveness. The effect of filling ratio on ground subsidence is simulated by changing the number of backfill particles in the goaf. (2) Porosity of backfill materials is an indicator to evaluate the compaction degree of backfill materials filled into the goaf. The effect of compaction degree of backfill materials on ground subsidence is simulated by changing the porosity of backfill particles.

Figures 19 and 20 are the scatter plots of the maximum subsidence values with different filling ratios and porosities. Simulation results show that filling ratio is the main factor that influences ground subsidence. Ground

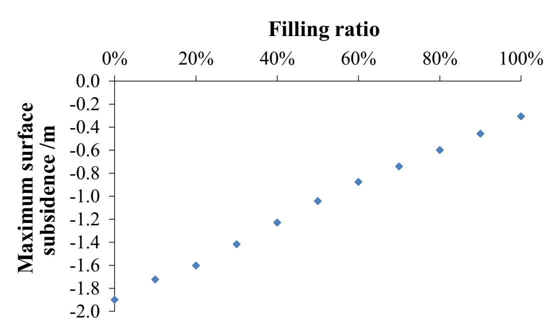

Fig. 19 Maximum ground subsidence values under different filling ratios

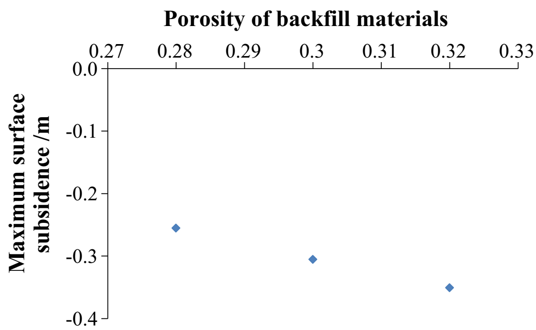

Fig. 20 Maximum ground subsidence values under different porosities

subsidence caused by solid backfilling mining increases rapidly with increasing filling ratio. The porosity of backfill materials affects ground subsidence secondarily. Ground subsidence caused by solid backfilling mining decreases with increasing porosity. The maximum ground subsidence value is 0.26 m when the porosity is 0.28 and increases to 0.35 when the porosity is 0.32. Thereby, adding a ramming mechanism at the back of the hydraulic support for fully mechanized solid backfilling mining is reasonable. The ramming mechanism that pushes and compacts backfill materials not only ensures that materials fill up the goaf to connect immediate roof but also improves the compaction degree of materials, which achieve the goal of ground subsidence control.

Conclusion

The overlying strata subsidence control is the key issue in the study of fully mechanized solid backfilling mining, which determines the success of backfilling mining. In this paper, a coupled method is applied to analyze the strata movement after backfilling mining. Discrete characteristics of backfill materials are simulated by discrete element simulation, and the continuous rock movement process is simulated by finite difference method. The socket I/O can be used to communicate between FLAC and PFC to accomplish the coupled analysis of discrete element–finite difference method medium. In this manner, a 2D numerical model is developed to obtain displacement and stress strata and backfill materials. The simulated backfilling mining agrees well with the field situation.

The coupled method is also used successfully to simulate and analyze the interaction among gangue backfill materials, overlying strata, and coal pillar, as well as the effect of the backfilling quality on subsidence control. The following conclusions can be drawn from the observed results of the coupled simulation.

1. In vertical direction, backfill materials help coal pillars share the partial load of the overlying strata, which contributes to the decrease of the abutment pressure of coal pillars and subsidence of overlying strata. In the horizontal direction, the increase in coal pillar strength is attributed to the lateral confinement provided by the backfill materials.
2. The filling ratio and the porosity of backfill materials affect the compaction characteristics of backfill materials significantly, and they are the key to control strata movement. In fully mechanized solid backfilling mining, the strata movement and ground subsidence over the backfilling working face are well controlled because the tamping mechanism pushes and compacts preliminarily backfill materials before being backfilled into the goaf to improve filling ratio and compaction degree.

The applied coupled discrete element–finite difference model provides a fundamental numerical framework to encourage further studies of strata movement controlling the effect of backfilling mining in different geological mining conditions to reduce the limitations of the current study.

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