Numerical study on mining induced mechanical behavior of a mine group controlled by a large geological body

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Abstract. In the present study, based on the geological information of the Yima Coalfield in Henan Province, People’s Republic of China, a numerical model composed of five mines with F16 large thrust fault and extremely thick conglomerate is constructed. Next, a self-developed parallel program, i.e. CASRock, is applied to simulate the mining process in different mines and investigate the associate mechanical behavior. The evolution of displacement, stress and plastic strain of rock mass under different mining conditions of the mine group in the Yima Coalfield are thoroughly demonstrated. The results reflect the interactions in mechanical behaviors between neighboring mines. These interactions are strengthened due to the existence of the overlying extremely thick conglomerate and F16 large fault. The stress transfer via the large geological body in large-scale goaf is the main reason for the high stress concentration of the adjacent working faces.

1. Introduction

Due to the great demand for coal resources, China’s coal mines have entered the stage of deep mining one after another. However, the geological environment and mechanical behavior of deep mines are complex, thus the prevention and control of rock burst dynamic disasters has become increasingly urgent [1]. After the coal mines entered deep mining, rock burst disasters caused by the mutual disturbance and influence between mines have gradually attracted widespread attention [2]. Due to the complexity of mine space relations and uncertainty of the geological conditions, the spatial structure and stability change of mine groups are extremely complex.

In regard to the mechanism and prevention of rock burst in deep mine, many scholars have made useful achievements [3], and have also carried out relevant research work on the mechanism and prevention of rock burst in roadway groups and coal seam groups. Su et al. carried out a study on the stability control of roadway group affected by the overhanging goaf [4]. Lu et al. performed an in-depth study on the mechanism of large deformation and instability of soft and broken roadway group and optimization of support technology in the Pan No. 2 Mine [5]. Pan et al. carried out a study on the mechanism and prevention of rock burst under static load in deep panel roadway groups [6]. Shi and Liu conducted a numerical simulation study on the rock burst mechanism of roadway groups [7]. Liu carried out research on the prevention technology of rock burst in dense roadway groups under deep dynamic pressure [8]. Yu has studied the prevention and control technology of rock burst in the Jurassic coal seam group of the Datong Mining Area [9]. According to the literature review, most of the related studies start from the stability of single mines and coal seams or roadway groups within a single mine to study the
occurrence law and control measures of rock burst, while there have been few studies on the time-space mechanical response behavior and mining disturbance mechanism of overburden structure between mines under the control of large geological bodies. The scale of mine cluster is typically in the order of magnitude of tens of km, thus falling within the scope of large-scale and multi-scale problems [10]. Under the condition of thick conglomerate bed roof, the intershaft stress caused by coal seam mining is bound to influence each other, while the high and thick hard rock bed is a special form of rock formation, which is widely distributed in many mining areas throughout China [11-16]. In this paper, a self-developed parallel numerical code, i.e. CASRock, is used to numerically investigate the mechanical behavior induced by coal seam mining of the mine groups in the Yima Coalfield, which is characterized by a large geological body. The interactions among the different mines are analyzed.

2. Introduction to CASRock software

2.1. Basic principles
CASRock is a self-developed cellular automata software for the engineering rockmass fracturing process, which is a combination of elasto-plastic mechanics, rock mechanics, fracture mechanics, engineering geology and cellular automaton. CASRock contains a series of previous developed numerical systems, namely EPCA for simulation of heterogeneous rock failure process, VEPCA for visco elastoplastic analysis, D-EPCA for rock dynamic response simulation, THMC-EPCA for coupled thermo-hydro-mechanical-chemical processes in geological media and RDCA for simulation of rock cracking process from continuity to discontinuity [17-21]. The system includes components such as cells and their state, cell space, neighbor and updating rule. A parallel cellular automaton updating rule was developed in CASRock to realize large-scale simulation based on CA and MPI algorithm (Fig. 1). The material properties of the cells are assigned, and certain constitutive relation and failure criteria are given to the cells. Next, the updating rule of cellular automata is used to update its state, so as to simulate the fracturing process of the coal and rock mass.

![Figure 1 Parallel CA updating rule](image)

2.2. Constitutive relation and failure criterion of cells
Under complex stress conditions, coal and rock mass may exhibit different mechanical behaviors, such as brittleness, strain softening, ideal plasticity or strain hardening. Therefore, in the CASRock software program, the constitutive relation of the cell unit is as shown in Fig. 2, and the appropriate constitutive relation can be selected according to the actual situation. CASRock includes Drucker-Prager, Rankie and Mohr-Coulomb and other typical failure criteria of coal and rock masses. For example, for the modified Mohr-Coulomb criterion, the Rankie criterion is adopted for tensile failure, while the Mohr-Coulomb criterion is adopted for shear failure (Fig. 3).
3. General situation of the Yima Coalfield

The Yima Coalfield is located in Yima City and Mianchi County, in the western part of Henan Province, covering an area of approximately 100 km². There are five production mines, respectively located in Yangcun, Geng Cun, Qianqiu, Yuejin and Changcun, along with an open pit mine in the coal field (Fig. 4). As a whole, the mine presents a very asymmetric synclinal structure, which begins from the concealed outcropping of the coal seam in the north, ends at the F16 reverse fault in the south, and is the sedimentation missing boundary in the east and west. The buried depth of the coal seam is 2~1,200 m. After decades of mining, the maximum mining depth has reached 1,060 m.

Extremely thick conglomerate occurs in the roof of the coal seam in most areas of the Yima Coalfield. The Qianqiu and Yuejin Mines have the greatest thickness, reaching up to several hundred m, with the thickest being more than 700 m (for interbedded sand and conglomerate, the thickest is nearly 900 m). A total of 107 rock bursts have occurred in the Yima Coalfield, including 37 in the Yuejin Mine, with serious rock bursts. The detailed statistics are shown in Table 1. The statistics reveal that the impact events mainly occurred in the area with large thickness of the hard rock layer in the roof, and close to the F16 fault [22].

| Mining depth | Frequency of rock burst | Yima Coalfield | Proportion | Yuejin Coal Mine | Proportion |
|--------------|-------------------------|-----------------|------------|------------------|------------|
| <600m        | 18                      | 17%             | —          | 0                | —          |
| 600m~700m    | 46                      | 43%             | 1          | 2%               | —          |
| 700m~900m    | 43                      | 40%             | 6          | 16%              | —          |
| ≥900         | 30                      | 81%             | —          | —                | —          |

4. Simulation analysis of mine group mechanical behavior in the Yima Coalfield

In order to analyze the mining mechanical behavior of the mine group under the control of a large geological body in the Yima Coalfield from a comprehensive perspective, CASRock was used to
conduct numerical modeling for the entire mining area, and the distribution characteristics of stress, displacement and plastic zone after mining of five mines were analyzed. The model consists of six rock strata and one large fault (Figs. 5 (a) and (b)). From top to bottom, the rock strata are in the following order (with the combination of thinner and weaker interbeds): extremely thick conglomerate, sand and gravel interbeds, mudstone, coal seam, clay rock and sandstone (Table 2). In the simulation, the initial stress field is first applied, then, after the stress has balanced, the goafs are mined all at once for the sake of simplicity, then the mechanical characteristics of the entire coal field are analysed.

According to the analysis of the in-situ stress test results, the direction of the maximum horizontal principal stress in the underground stress field of the Yima Coalfield is close to the east and west, while the underground stress of the Yima Coalfield is a $\sigma$-type upper stress field. Among them, the in-situ stress level of the Qianqiu Mine is categorized as a medium and slightly high in-situ stress area in the quantitative value, which is basically the average value of the in-situ stress of the five mines. Therefore, the in-situ stress boundary imposed by the numerical model shall be subject to the in-situ stress value of the Qianqiu Mine. The boundary constraints in the X and Y directions are applied respectively, then the trapezoidal boundary load conditions are applied according to the field measured in-situ stress results. The maximum stresses in the X and Y directions of the model are 9.32 MPa and 18.01 MPa, respectively. A fixed boundary constraint is applied at the bottom of the model in the Z direction, the top is the free end, and a gravity load condition is applied. The hardware and software used are Windows Server 2008 R2 Enterprise Edition, Intel(R) Xeon(R) CPU E5-2687W v4 processor (2 cores), with a frequency of 3.00 GHz, 48 CPU processors, 256 GB internal memory and a 64-bit operating system. The model is discretized into a system composed of approximately 12 million cell units, and 45 processors are used for parallel computation. Fig. 5(c) lists the results of the parallel partitioning.

![Figure 5](image)

**Figure 5.** (a) Simplified goaf in the modeling; (b) stratum group of the simulation model; (c) parallel district method (coordinate scale unit: m)

**Table 2.** Model parameters of coal rock physical and mechanical properties

|                     | $\gamma$ /t/m³ | $\sigma_t$/MPa | $\sigma_c$/MPa | $E$/GPa | $\mu$ | $C$/MPa | $\Phi$ /° |
|---------------------|----------------|----------------|----------------|---------|-------|---------|----------|
| Conglomerate        | 2.73           | 2.56           | 57.03          | 31.83   | 0.36  | 21.12   | 43.40    |
| Sandstone and      | 2.59           | 2.23           | 48.11          | 10.23   | 0.35  | 17.50   | 37.11    |
| conglomerate        |                |                |                |         |       |         |          |
| interbedding        |                |                |                |         |       |         |          |


Fig. 6(a) shows the initial distribution of in-situ stress field after stress balance. CASRock can accurately reflect the distribution law of vertical stress from shallow to deep, and from small to large (the compressive stress is negative). As it is affected by surface elevation, the surface stress field presents non-uniform distribution characteristics. Due to the presence of large faults, stress concentration appears in the local stress field, which can also be seen more clearly from the distribution of the stress field in the typical section in Fig. 6(b).

The model can be sliced to better understand the internal mechanical characteristics. Figs. 7 and 8 show the vertical stress field distribution, displacement distribution and plastic zone distribution of slices at different positions in the X and Y directions after the mining of five goafs. As can be seen from the vertical stress distribution (Figs. 7(a) and 8(a)), compared with the stress field before mining (Fig. 6(a)), the existence of goaf stress field caused by the non-uniform distribution of goaf roof and floor vertical stress release, and two sides and face appeared in front of the stress concentration, and the adjacent face with different width of coal pillar. In addition, the stress concentration degree is also different, and a phenomenon of mutual disturbance is present. Figs. 7(b) and 8(b) are the total displacement vector distribution after the formation of the goaf, which better reflects the surface deformation caused by mining. The larger the goaf is, the more significant the surface deformation will be. In the Y direction of each section in Fig. 7 (b), with the increase of Y, the buried depth of the coal seam is relatively shallow, and the displacement of overlying rocks and surface is large. Fig. 8(b) shows a similar rule in the range of x=15,000~20,000 m. This indicates that the superthick conglomerate overlying the shallow coal seams in the western and northern areas of the mine exhibit no suspended roof, while the superthick conglomerate in the eastern and southern areas of the mine is in a suspended roof state. Figs. 7(c) and 8(c) show the strain distribution in the plastic zone. It can be seen from the roof and floor of the goaf that the two sides and the front of the working face are the parts with exhibiting more serious damage (red dotted circles), and that bed-separation damage occurs in some places, which is consistent with the actual situation. When X=1,000 m, 4,000 m and 7,000 m in Fig. 7(c), the plastic area above the goaf partially develops to the surface, while the plastic area above the deep slice goaf is not connected with the surface. In Fig. 8(c), the plastic area is larger in the range of 3,000~7,000 m and smaller in the range of 18,000~21,000 m. The simulation results reveal that the mechanical behavior of the Yangcun Mining Area is significantly affected by the F16 fault, while the mechanical behavior of the Yuejin Mining Area near the fault is not only affected by the fault, but also by the overlying super-thick conglomerate.

| Material        | Initial Stress (MPa) | Middle Stress (MPa) | Shear Stress (MPa) | Plastic Stress (MPa) | Friction Angle (°) |
|-----------------|----------------------|---------------------|--------------------|----------------------|--------------------|
| Mudstone        | 2.66                 | 2.61                | 35.77              | 17.66                | 0.14               |
| 2-1 coal seam   | 1.49                 | 0.74                | 11.76              | 2.18                 | 0.34               |
| Clay rock       | 2.52                 | 2.13                | 44.15              | 13.86                | 0.25               |
| Sandstone       | 2.59                 | 4.58                | 95.87              | 24.21                | 0.20               |
| F16 fault       | 0.15                 | 0.07                | 1.18               | 0.22                 | 0.34               |

**Table:**

The model can be sliced to better understand the internal mechanical characteristics. Figs. 7 and 8 show the vertical stress field distribution, displacement distribution and plastic zone distribution of slices at different positions in the X and Y directions after the mining of five goafs.
Figure 7. Mechanical characteristics of slices in different positions in the x direction after mining in the coalfield (coordinate scale unit: m); (a) vertical stress field distribution (stress unit: Pa); (b) total displacement vector distribution (displacement unit: m); (c) plastic zone distribution.

Figure 8. Mechanical characteristics of slices in different positions in the Y direction after mining in coalfield (coordinate scale unit: m); (a) vertical stress field distribution (stress unit: Pa); (b) total displacement vector distribution (displacement unit: m); (c) plastic zone distribution.

Fig. 9 shows the vertical stress distribution and plastic deformation distribution curve of the entire coalfield along the two sampling lines of the east-west coal seam, reflecting the non-uniform distribution of...
stress and plastic deformation following the formation of the goaf. After mining, the weight of the unbroken super-thick conglomerate in the mining area is assumed by the residual coal pillar. Due to the fact that the shallow coal resources in the mining area have been fully mined (Fig. 9(a) y=5,800 m), the stress of the residual coal pillar under the condition of super-thick conglomerate coverage increases sharply, reaching as much as 2.5 times the initial vertical stress. For deep coal mining, the super-thick conglomerate roof leads to the stress transfer to the coal pillar and unmined body. The coal pillar stress shows little difference from the shallow coal pillar stress, while the vertical stress of the unmined body is slightly higher than the initial vertical stress before mining. The high vertical stress of the coal body increases the likelihood of impact.

**Figure 9.** (a) Vertical stress distribution of coal seam at section y=2,252 m and y=5,800 m and comparison of vertical stress before mining; (b) Plastic strain distribution of section y=2,252 m and y=5,800 m

### 5. Concluding remarks

In this study, the mine group model of five mines containing the F16 fault and extremely thick conglomerate in the Yima Coalfield is constructed. The large-scale scientific simulation analysis of the mine group’s mining stability is carried out by means of a self-developed numerical tool, i.e. CASRock, a parallel program. Through the distribution characteristics of stress field, displacement field and coal rock failure area following the formation of goaf in the mine group, the influence of thick conglomerate and fault on the impact risk of mine group is observed. According to the simulated stress in the mining process of the mine groups, the stress transfer of extremely thick conglomerate overlying the large-scale goaf is shown to be the main cause of the high stress concentration of the adjacent working faces.

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