Study on the integrated planning of deep mining considering rock burst prediction

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Abstract. Deep mining is an inevitable future trend involving resource acquisition. However, as mining depth increases, the high geostress and severe mining disturbance lead to prominent rock burst disasters. At present, the design of deep mines is mainly based on the engineering experiences based on shallow mining. To date, no integrated planning has been implemented for deep mining in domestic mines. Moreover, during the deep mining process, most problems are handled and solved only after the disaster happens due to the lack of understanding of deep disaster problem. In this paper, a large-scale 3D numerical model was established by Map3D software by considering the high geostress environment, the physical and mechanical parameters of rocks, the constitutive model, and preliminary design parameters. Based on this model, the disturbance coefficient and energy accumulation state of stopes was predicted, and the rock burst risk was evaluated. According to the analysis results, the medium-deep hole sublevel open stopping method was chosen to reduce the rock burst risk during deep mining. Through the integrated planning of deep mining, the risk of rock burst disasters can be evaluated ahead of time, thus facilitating the use of a more scientific and reasonable mining method in the field of mining engineering. Integrated planning provides a new method for deep mining and can also and can help reduce or even control fundamentally the magnitude and frequency of rock burst disasters. Thus, it has great security and economic significance for mining engineering.

1. Introduction

The demand for mineral resources is continuously increasing, inevitably leading to the trend of deep mining. The geological environment in deep mining is very complicated and is obviously different from the shallow environment. High geostress is the primary expression of deep mining condition and is also the major cause of rock bursts and other deep disasters. Rock bursts generate huge safety and economic damages, making it a major threat in the field of deep mining. The rock burst problem was first reported in England in 1738. Since then, problems related to rock bursts have yet to be effectively resolved. At present, the main method in dealing with rock bursts is the supporting structure and system. Zuo et al. investigated the matching relationship between bolt diameter and borehole diameter and discovered the bolt supporting effect in the mining roadway [1]. By studying the mechanical characteristics of the support system under impact loads along with the underlying damage mechanisms, Wu et al. improved our scientific understanding of the performance and design of rock bolt support systems in coal burst-prone mines [2]. Aydan conducted numerical, theoretical, and experimental studies on rock bolts and rock anchors under shaking and impulsive loading [3].
However, to some extent, the above-mentioned methods are passive, blind, and post-event treatments. These may cause secondary economic losses, because the supporting structures are always excessive compared with the reasonable standard. Moreover, by using these methods, it is still not possible to avoid rock burst disasters before conducting mining activities. Thus, integrated planning is proposed as a new idea for deep mining. Through the macroscopic and strategic planning of mining activities, the mining method and sequence can be optimized, thus facilitating the advanced prediction of the magnitude and frequency of rock bursts. However, research on the integrated planning of deep mining is still in the primary stage at the moment. Some scholars have realized the significance of integrated planning and have made some attempts to investigate the issue [4–6]. The integrated planning provides a new and positive method for the early deployment and active prevention of rock bursts from the source.

In the study of rock burst prediction, scholars have also proposed many theories and models. For example, Adoko et al. used a knowledge-based and data-driven fuzzy model to predict rock bursts [7]. Gao gave a forecasting of rock bursts on the basis of abstraction ant colony clustering algorithm [8]. Zhou estimated the feasibility of stochastic gradient boosting approach and predicted the rock burst damage in burst-prone mines [9]. Guo et al. (2017) raised a progressive mitigation method of rock bursts under complicated geological conditions [10], while Kornowski and Kurzeja adopted the expert method to confirm the seismic energy and factors, which they used for the rock burst probability prediction [11]. Sirait et al. investigated the energy balance and induced stress to predict the rock burst of a cut and fill mine [12]. Feng et al. analyzed the fractal behavior of the microseismic energy associated with immediate rock bursts in deep, hard rock tunnels [13], and Wang et al. focused on the characteristic energy factor of the deep rock mass under weak disturbance [14]. Jiang et al. took a buried tunnel with a depth of 2500 m as an example and studied its rock burst characteristics through a new energy index [15]. Guo and Li proposed a linear elastic energy criterion to analyze rock burst tendency in deep rock mass [16]. Xie et al. conducted energy analysis on damage and catastrophic failure of rocks [17], while Xu et al. studied a new energy index to evaluate the tendency of rock burst and applied it to the field of engineering [18]. Among these meaningful studies, energy index and parameters present great advantages in terms of efficiency, convenience, and accuracy, and can be adopted in the integrated planning of deep mining for rock burst prediction.

In the current paper, a large-scale 3D numerical model was established by Map3D software while considering the rock physical and mechanical parameters, the constitutive model, the high geostress environment, and the preliminary design parameters. Based on this model, the energy accumulation state of stopes was quantized, so that the rock burst hazard risk could be estimated. Therefore, to reduce the rock burst risk during deep mining, a much safer mining method was chosen after comparison. Results revealed that through integrated planning, the risk of rock burst disaster can be evaluated ahead of time by adopting a more scientific and reasonable mining method. Integrated planning for deep mining is very meaningful in reducing the risk of rock burst; it can also provide scientific foundation to ensure safe, efficient, and green mining in the future.

2. Engineering and simulation parameters in integrated planning

The study of integrated planning is based on the Jiawula Pb-Zn-Ag Mine located in Neimenggu Province, China. The whole ore body is buried 800 m below the earth's surface.

2.1. Mining methods and stope parameters

Given that the orebody is very steep and narrow, two mining methods are initially selected according to the technical mineral and geological conditions: the medium-deep hole sublevel open stoping method and the shallow hole shrinkage mining method. The mining sequence is from top to bottom at different levels and every other one for single level.

The ore blocks included stope rooms and pillars, which were arranged adjacent to each other. For the two methods, both ore blocks had the same size: length of 42 m, width (thickness of the ore body) of 4 m, and a height of 37 m.
2.2. In situ geostress and rock mechanical parameters

The geostress data are acquired from the in situ measurement, and the respective fitted formulas are expressed as

\[
\sigma_{h,\text{max}} = 0.0446H - 0.0695, \quad (1)
\]

\[
\sigma_{h,\text{min}} = 0.0296H + 0.7481, \quad (2)
\]

\[
\sigma_v = 0.0271H - 0.0741, \quad (3)
\]

where \(H\) is the depth, and \(\sigma_{h,\text{max}}, \sigma_{h,\text{min}},\) and \(\sigma_v\) represent the maximum horizontal principal stress, minimum horizontal principal stress, and vertical principal stress, respectively.

The maximum depth of the model is 560 m, which means that the values of the three principal stresses are 24.9065, 17.3241, and 15.1019 MPa, respectively. The kind of rock used in the model is andesite, which is found in the simulation area. The basic mechanical parameters of andesite were obtained by performing the in situ drilling and physical and mechanical property test on rocks, as shown in Table 1.

Table 1. The parameters of andesite in the simulation.

| Parameter                      | Value  |
|--------------------------------|--------|
| Uniaxial compressive strength (MPa) | 126    |
| Tensile strength (MPa)           | 6.65   |
| Cohesion (MPa)                   | 9.39   |
| Internal friction angle (°)      | 40.1   |
| Elastic modulus (GPa)            | 55.3   |
| Poisson's ratio                  | 2.26   |

3. Integrated planning and rock burst prediction analysis

3.1. Large-scale 3D numerical model

A large-scale 3D numerical model was established by Map3D software in order to conduct the integrated planning and estimation of the rock burst. For the two mining methods, two mining levels and six mining rooms were included. The in situ geostress condition and rock mechanical parameters were adopted in the numerical model. The excavation sequences for the mining rooms are shown in Figure 1 and Figure 2. The Mohr–Coulomb Criterion was employed. The 3D model and the cross sections to be studied are shown in Figure 3.
Figure 3. 3D numerical simulation model with six chambers in Map3D.

3.2. Numerical analysis on disturbance coefficient
After simulation, the minimum principal stress contours for both mining methods are acquired and displayed.

Figure 4. Minimum principal stress contour for the shallow hole shrinkage mining method.

Figure 5. Minimum principal stress contour for the medium-deep hole sublevel open stoping method.

As shown in Figures 4 and 5, the range of disturbance stress (i.e., the accumulated stress in the interval pillars and the released stress in the roof pillars) of the shallow hole shrinkage mining method is a little wider than that of the medium-deep hole sublevel open stoping method. Moreover, the corresponding maximal accumulated stress values in the interval pillars are 24.853 and 24.760 MPa. Here, we define the ratio of maximal accumulated stress to the vertical principal stress as the disturbance coefficient. Accordingly, we calculate the disturbance coefficient values to the geostress as 1.645 and 1.640, respectively.

3.3. Numerical analysis on energy accumulation
After simulation, we obtained the accumulation energy contours for both mining methods, as shown in Figures 6 and 7. By performing a comparative analysis of the simulation results in Figures 6 and 7, we can easily find that the accumulation energy in the shallow hole shrinkage mining method is larger than that in the latter method. Especially for the high level energy accumulation area in the roof pillars, the values for both methods are 171.294 and 162.169 kJ, respectively.
Figure 6. Accumulation energy contours under the shallow hole shrinkage mining method.

(a) Whole contour
(b) Energy value < 40 kJ
(c) 40 kJ < Energy value < 100 kJ
(d) 100 kJ < Energy value < 200 kJ

Figure 7. Accumulation energy contours under the medium-deep hole sublevel open stoping method.

(a) Whole contour
(b) Energy value < 40 kJ
(c) 40 kJ < Energy value < 100 kJ
(d) 100 kJ < Energy value < 200 kJ

3.4. Rock burst estimation discussions
The disturbance coefficient analysis reveals that the two values of both mining methods are not far apart. The disturbance coefficient under the shallow hole shrinkage mining method is a little bigger than that of the medium-deep hole sublevel open stoping method. However, there is a difference between the two mining methods in terms of the energy accumulation analysis. According to the strain energy theory, the higher accumulation energy means the higher rock burst tendency of the host rock. Following the principles and aims of integrated planning, the rock burst risk is considered as the decisive factor. Therefore, to ensure the safety of deep mining, the medium-deep hole sublevel open stoping method is suggested in this case.

A much safer mining method can be provided by comparing the rock burst tendencies of two mining methods before excavation activities. Therefore, the risk of rock burst can be reduced ahead of time by large-scale integrated planning, thus providing valuable guidance for mining engineering.

4. Conclusions
In this paper, a new method of integrated planning was proposed, and a mining case was numerically analyzed by Map3D software. The rock burst tendency was estimated before the excavation activities, thus showing the advantages of integrated planning. The main conclusions of this study are as follows:
In order to conduct an integrated planning study, a 3D numerical model was established by adopting the in situ geostress conditions and rock mechanical parameters. By large-scale numerical modeling, the excavation responses of the shallow hole shrinkage mining and the medium-deep hole sublevel open stoping methods were predicted. Moreover, the disturbance coefficients and accumulation energies of both mining methods were acquired through analysis. Moreover, comparing their disturbance coefficients, 1.645 and 1.640, showed little difference, but the energy accumulation value of the medium-deep hole sublevel open stoping method is smaller than that of the other mining method, with the values of 162.169 and 171.294 kJ, respectively. According to strain energy theory, a higher accumulation energy means a higher rock burst tendency of the host rock. Therefore, the medium-deep hole sublevel open stoping method is recommended in this case for safety reasons. Through integrated planning, the risk of rock bursts can be evaluated ahead of time so that a more scientific and reasonable mining method can be applied—a development that has great security and economic significance for mining engineering.

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