Overall Design and Optimization of Mining Sequence in High-Stress Environment of Thick Orebody

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Abstract. After entering deep mining, the stress concentration level because of engineering excavation is considerably greater than the strength of the engineering rock mass. Here, we consider the engineering impact of a high stress environment in the deep mine plan, integrate the high-stress environment and its evolution with the mining process into the mining plan, and realize the balance of improving the stress state and getting the maximum net present value. Using Map3d boundary element simulation software, we planned two vertical and four horizontal mining sequences for deep and thick orebody backfill mining, respectively, and then analyzed the changes in stress and rock mass energy because of mining disturbance. The results show that the surrounding mining sequence can effectively improve the mining stress environment and increase production capacity. Using large-spaced dispersion and mining sequence from the middle to both ends can gradually redistribute the stress to adjacent areas, thus reducing the degree of stress concentration.

1. Introduction
In deep mines, changes on the technical conditions and environment were observed. Both vertical original rock stress because of gravity and stress concentration level because of engineering excavation are greater than the strength of the engineering rock mass, i.e., >20 MPa and >40 MPa, respectively [1]. The deep plateau rock stress and the secondary stress field because of mining disturbances make the deep quarry layout, mining sequence, and stope structure parameters different from shallow mining. Note that the shallow mining method will not be completely applicable to deep mining [2].

With the development of computer applications, the use of numerical simulation technology has been increasingly widely used in the mining sequence of underground mining and optimization of stope structure parameters. FLAD3D and ANSYS are commonly used software that mostly use the finite element method to calculate and discrete in the entire solution domain, resulting in a large degree of freedom of the problem and the original information. Thus, the infinite domain can only be artificially considered as a finite domain; however, the discrete technique of the finite element method has its flaws. It simulates the originally continuous medium with a set of finite elements connected only at the nodes. This introduces both discrete errors and continuous between the elements. When the requirements are high, the construction of finite elements is often difficult. However, the boundary element method is a unique new numerical method after the finite element method. Compared with the finite element method, the boundary element method is only discrete on the boundary, which reduces the number of numerical calculations by one dimension and reduces the freedom of the problem and the amount of original information [3,4].
In this study, for the mining of thick ore bodies under deep high-stress conditions, we constructed the inverted V and positive V mining mechanics models as well as analyzed the stress transfer law and rockburst risk characteristics under different mining sequences. The high-stress environment and its evolution law along with the mining process are integrated into the deep mining planning, as well as an economic evaluation model for the overall planning of deep well mining to realize the value of resource development investment and variable mining depth is constructed to form the deep environment and mining system.

2. Design and layout of thick ore body mining under high-stress conditions

Usually, the metal mining sequence is divided into inverted V and positive V mining sequences, as shown in Figure 1. Positive V mining has the advantages of saving initial investment and high mining safety. It is extensively used in deep mines abroad; however, it often requires the reservation of horizontal ore pillars, leading to difficulties in the connection between the upper and lower stages of production and limiting mine production capacity. Inverted V mining is primarily used in shallow mining because of limitations such as large initial investment, extended construction period, and the slow recovery of funds [5].

![Figure 1](image1)  
**Figure 1.** Design plan for the mining sequence in the vertical direction: (a) reverse V mining sequence and (b) positive V mining sequence

As per the influencing factors of the production process, production capacity and mining engineering aspects of the post-filling mining method is often used in thick ore bodies. Following the theory of destressing, the horizontal mining sequence is usually mining one by one or mining every third. The mining direction is from one end to the other end or from the middle to both ends; the mining room and the pillar are mined in steps [6]. Figure 2 shows several mining sequences in the horizontal direction.

![Figure 2](image2)  
**Figure 2.** Horizontal mining plan design plan: (a) mining one by one, from one; (b) mining every third, from one end to the other end; (c) mining from one by one, from the middle to both ends; and (d) mining every third, from the middle to both ends

Certain key issues that restrict the safe and efficient development of deep mineral resources are the rockburst risks (caused by high stress in deep wells) and long infrastructure periods and the slow recovery of funds (caused by high well depths). A reasonable sequence of mining deposits is
conducive to improving the stress distribution of the underground space and controlling the degree of overlap of stress increase zones because of the dynamic mining process [7] while obtaining the maximum economic benefits for the mine and realizing the investment value.

3. Stress prediction in the overall planning model

3.1. Simulation solution

3.1.1. Stope layout
Mining of mine is divided into multiple steps: mining, cutting, blasting, and filling mining. The process of mining is a continuous operation. Only when a mining unit is completely mined, it will then enter the next mining unit; thus, each mining unit should be wholly completed. Using Map3d software, we built an orebody model mined to a depth of 1500 m, as shown in Figure 3. The model includes 390 stopes, has a 15 m × 30 m × 50 m size of each stope, and has a 195 m × 180 m × 300 m size of the mining body.

3.1.2. Mechanical parameters
First, we selected the physical and mechanical parameters of a domestic copper mine ore rock [8], as shown in Table 1.

| Type          | Uniaxial compressive strength (MPa) | Cohesion (MPa) | Internal friction angle (°) | Modulus of elasticity (GPa) | Poisson's ratio |
|---------------|-------------------------------------|----------------|-----------------------------|-----------------------------|-----------------|
| Ore body      | 174.89                              | 29.54          | 50.85                       | 85.20                       | 0.296           |
| Filling body  | 2.06                                | 0.7013         | 29.4                        | 0.34                        | 0.27            |

According to the measurement results of in-situ stress of the copper mine [9], the rules of vertical stress and horizontal stress varying with depth are as follows:

- vertical stress: \( S_v = 0.0259H - 0.865 \)
- maximum horizontal principal stress: \( S_1 = 0.0249H + 6.809 \)
- minimum horizontal principal stress: \( S_2 = 0.0207H - 0.458 \)

We simulated and analyzed the stress changes at a depth of 1500 m; therefore, the selection of the original rock stress value was selected as the maximum horizontal principal stress of 44.159 MPa, the minimum horizontal principal stress of 30.592 MPa, and the vertical stress of 37.985 MPa.

![Orebody model and initial stress](image)

3.2. Stress analysis and prediction of vertical mining sequence
3.2.1. Reverse V mining sequence
The most commonly used mining sequence in shallow mining is the inverted V order. As shown in Figure 4, the one-step stope is produced under high-stress conditions, and the roof is in the stress concentration area, reaching 50–60 MPa, which is not conducive to operational safety. The two-step stope will be mined under low-stress conditions or yield conditions. Support measures are then required for areas with rockburst tendencies, increasing mining costs.

Figure 4. Maximum principal stress cloud diagram of the inverted V mining sequence

3.2.2. Positive V mining sequence
The cloud diagram of the change of the maximum principal stress of the deep positive V mining process is shown in Figure 5. With the advancement of the mining, the high-stress level area of the stress redistribution because of the mining disturbance is gradually moved to the periphery of the entire area. However, a relatively relaxed and fractured area is immediately formed after the mining operation area. This stress relief area is directly below the current mining area, and the stope is located under the filling body rather than in the high-stress rock area. The two-step mining provides a relatively safe working environment, avoids the mining workers working under the exposed area, and improves the safety of mining.

Figure 5. Maximum principal stress cloud of positive V mining sequence

3.3. Stress analysis and prediction of horizontal mining sequence
According to the design plan of the horizontal mining sequence, as shown in Figure 2, the stress evolution laws of the four horizontal mining sequences are obtained using simulation calculation, as shown in Figure 6. On the basis of the above four mining schemes, after the first step of excavation, the stress is concentrated around the excavated mine house. After excavation and unloading, the roof of the excavated mine house is in a lower stress state. The stress value of the “mining every third” method is significantly lower than that of the “mining one by one” method; i.e., the concentration of stress generated by mining with the “large interval scattered layout” method is significantly lower than that of the “mining one by one” centralized layout. The mining sequence from “middle to both ends” is beneficial to improve the stress distribution of the ore pillar, i.e., the two-step stope, and to reduce the stress concentration of the ore pillar. Therefore, through comprehensive analysis, the principles of horizontal mining sequence optimization that are beneficial to mining site pressure management mainly include the following.

1) The degree of stress concentration generated by mining in the “large-area dispersed
arrangement” method is significantly reduced.
(2) The way from the center to the surroundings can gradually shift the redistributed stress to the adjacent area.

Figure 6. Maximum principal stress cloud of different mining sequences in the horizontal direction: (a) mining one by one (from one end to the other end), (b) mining every third (from one end to the other end), (c) mining one by one (from the middle to both ends), and (d) mining every third (from the middle to both ends)

4. The mining risk assessment method of the overall planning model

4.1. Stable state of deep mining rock mass and rockburst prediction index
Under the action of deep high stress, the instability of mining rock mass has become complicated and changeable, which is primarily manifested in the appearance of plastic flow state, leading to shear expansion and failure. Note that mining and destressing action lead to the rapid release of energy, and the hard rock suddenly breaks. Therefore, when evaluating the instability mechanism of the deep rock mass, in addition to the conventional factors such as stress, strain, and plastic zone of shallow mining, factors such as plastic flow and energy change of the surrounding rock should be considered. Thus, a comprehensive evaluation of deep rock mass instability mechanisms based on various factors should be systematically considered. Usually, this is performed using elastic release energy, local energy release rate, volume, depth and range of plastic failure zone, overall displacement and key point displacement, and overall stress distribution and stress concentration and stress release of key parts [10,11]. We used the Map3d software to predict the eccentric stress value and eccentric stress intensity during the mining process, to determine the rockburst tendency, and to predict the rationality of the
planning [12].

4.2. Dynamic analysis of deviatoric stress
Following the relationship between rock mass failure and standard deviatoric stress, the Canadian Creighton mine established stress risk limits based on historical information and experience (Table 2), which were used to assess stress risk levels [13].

Table 2. Stress hazard map for a vertical section at Vale's Creighton mine

| Stress Hazard    | Anticipated stress conditions-rock mass/seismic response                                                                 |
|------------------|-------------------------------------------------------------------------------------------------------------------------|
| Very low         | Minimum stress hazard: in-situ to low-stress conditions \((\sigma_1-\sigma_3)/UCS < 0.4\)                                  |
| Low              | Damage initiation small magnitude event \([0.4 \leq (\sigma_1-\sigma_3)/UCS < 0.5]\)                                       |
| Medium/High      | Increased likelihood of moderate to large events \([0.5 \leq (\sigma_1-\sigma_3)/UCS < 0.7]\)                             |
| Very high        | Maximum likelihood of very large magnitude events \([(\sigma_1-\sigma_3)/UCS \geq 0.7]\)                                 |

In Figure 7, the calculation result of the partial stress intensity ratio of the positive V mining sequence process is shown. With the continuous excavation of the stope, the second step stope extends from a small to a medium degree of the rockburst risk area. With the continuation of mining, the rockburst risk zone gradually migrates to the surrounding rock, the scope of the risk zone gradually increases, and the stress risk value gradually increases. The rock mass three-dimensional mechanical environment evaluation model to judge the rockburst risk level can provide a reliable theoretical basis for the optimization of the support design of the mining roadway and the prediction of the dangerous area.

![Figure 7. Deviatoric stress of positive V mining sequence](image)

5. Cooperative evaluation of the evolution characteristics of deep mining stress and mining economy
During the mining process, because of different mining methods, the mining volume, ore output, mining and cutting engineering volume, ore grade, loss rate, and depletion rate are different. Therefore, different mining methods and mining sequences for an ore block will have different mining costs, which is divided into direct mining cost and uncertain cost. According to the operation process, direct mining cost primarily includes development engineering cost, mining and cutting engineering cost, rock drilling operation cost, blasting cost, mining cost, ventilation cost, and filling cost. The uncertain cost is calculated through the uncertainty analysis of the mining process. The probability of underground disasters increases as the depth mining increases. Stress concentration in the mining process is likely to cause rock bursts. Corresponding support measures are taken according to the rockburst risk level, to estimate the corresponding support costs, and hence, this is the uncertain cost [14].

Production cost is a function of the mining depth \(H\) and the total output \(A\), including the direct mining cost and uncertain disaster cost of each production system link of the mine, namely,

\[
C_{pt}(H, A) = \sum_{i=1}^{n} C_i
\]
where $C_{pt}(H,A)$ is the cost per ton of ore and $C_i$ is the production cost per ton of each production system link in mining, in which $C_1$ is the cost per ton of expenditure engineering; $C_2$ is the cost per ton of cut engineering; $C_3$ is the cost per ton of rock drilling and blasting; $C_4$ is the cost per ton of filling; $C_5$ is the cost per ton of transport; and $C_6$ is the uncertain cost.

$$C_i = a_i + b_i(H-H_0)(i=1,2,\ldots,5) \tag{2}$$

In Eq. (2), $a_i$ is the cost not related to mining depth and sequence; $b_i$ is the cost when the unit mining depth increases, the corresponding project increase; $H$ is the depth of mining; and $H_0$ is the base depth of mining assumed in the calculation of production costs, which is used as a basis to analyze the changes in mine production costs when the depth changes.

According to the assessment of different rockburst risk levels, the supporting areas and supporting methods and the corresponding supporting design parameters are provided, which is conducive to the stability control of the surrounding rock of the mining roadway and achieves regionalized fine support design. The corresponding support mode is selected according to the corresponding capacity absorption value of different support components. The uncertain cost incurred by the support is calculated according to Table 3 [15].

| Description                      | Specification | Peak load   | Limit deformation | Absorb energy |
|----------------------------------|---------------|-------------|-------------------|--------------|
| Resin anchor bolt                | 19 mm         | 120–170 kN  | 10–30 mm          | 1–4 kJ       |
| Pipe joint anchor (FS-46)        | 46 mm         | 90–140 kN   | 80–200 mm         | 5–15 kJ      |
| Correct tapered anchor           | 16 mm         | 50–100 kN   | 100–200 mm        | 10–25 kJ     |
| Anchor rope                      | 16 mm         | 160–240 kN  | 20–40 mm          | 2–6 kJ       |
| Welded steel mesh                | 4 × 4         | 34–42 kN    | 150–225 mm        | 3–6 m$^2$    |
| Shotcrete and welded steel mesh  | Two-layer net | Smaller than a single-layer net | Three- to five-layer net absorption capacity |

6. Dynamic optimization during the full life of the mining process

The rockburst risk level is determined according to the 3D mechanical environment evaluation model of the rock mass, which provides a reliable theoretical basis for the optimization of the support design of the mining roadway and the pre-judgment of the dangerous area. As shown in Figure 8, through the reciprocal relationship between the 3D mechanical environment and economic evaluation, the dynamic regulation during the full life of the mining process is realized.
7. Conclusion and outlook

In this study, we consider the high-stress environment of deep mine and its evolution law along with the mining process as constraints. To realize the investment value of mine resource development, the principles and methods of the overall planning of deep metal mining are established to achieve the planning and control of the whole process of deep metal mining. Compared with the “mining one by one” method and inverted V mining sequence in the shallow mining, the “large interval and dispersed arrangement” method of the thick and large ore body in the deep mining and the positive V mining sequence from the center to the surrounding can be redistributed. The stress is transferred to the adjacent area, greatly reducing the safety risk of the operator. Two stopes can only produce the positive V type mining sequence at a specific level, and the mining efficiency is low. On this basis, the mining sequence can be optimized further; however, it generally still adheres to the principle that the center shifts the stress peak to the surroundings, gradually transfers the stress, and actively creates more unloading areas.

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