Numerical Optimization of Hidden Edge Stope Mining in Underground Metal Mines

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Abstract. In a metal mine, there was a great risk of mining hidden resources due to unreasonable mining in the early stage. In order to effectively and safely mine this part of the resources, with the displacement as the objective function, a preliminary optimal dynamic programming model for the mining sequence of the unstable collapse zone was established and determined the preliminary plan. Using numerical analysis methods to optimize the mining sequence of the stope in the unstable collapse area. The results show that: 1) From the dynamic programming model, four feasible preliminary schemes are determined from the 10 schemes of possible mining sequence according to the numerical analysis results; 2) Mining from the S1-2# stope is the most reasonable. After comprehensive judgment, the optimal mining order of hidden danger stope is from S1-2# to N1-2# and then S1-1#. The next order is from N0-1# to S0-1# and 0#. The research’s results could provide reference for safe mining of similar mines.

1. Introduction

Mineral resources were essential for economic construction and development and were non-renewable. Due to historical and technical conditions, most mines had previously exploited mineral resources with high grade and easy exploitation [1]. In order to meet the stable development of mineral resources, in the continuous innovation of technical conditions, in addition to the deep extension of mineral resources, it was necessary to fully recover the hidden resources left by mining due to various reasons [2]. In particular, a series of complex engineering problems such as the surrounding rock gangs, the structural damage of the rock mass and the instability of the dike chamber caused by the instability and collapse of the mining site in the early stage of mining had brought significant safety hazards to further mining [3]. Due to the particularity of this kind of hidden danger resources, the stope range affected by the instability and collapse of the stope was often large, and the geological conditions and mining conditions of the ore body would become extremely complicated [4]. Throughout the previous research and engineering examples, in mining hidden danger resources, there was no fixed method for the recovery plan. The reasonable and safe mining methods were determined by the situation at the scene, that was, the specific situation was analyzed in detail, and there was no standard to follow, and the overall exploitation of hidden resources. The overall idea of hidden danger resources was to constantly improve its mining plan during exploration, including determining the approximate instability collapse range. Under the condition of ensuring the stability of surrounding rock, effective control of ground pressure was the key to solve such problem [5–7].
It was a key step to optimize the mining sequence of the stope in the unstable collapse zone to achieve safe recovery of hidden danger resources. According to the complicated mining technical conditions of the collapsed area and the distribution characteristics of the stope in the unstable hidden danger area, the displacement was taken as the objective function, the preliminary optimization dynamic programming model of the mining sequence was established, and the preliminary scheme was determined, and the numerical method was adopted to finally realize the mining sequence optimization.

2. Status of mining of hidden danger resources at the edge of unstable collapse area

After the mining of the lower part of the 0# stope of a metal mine was about 22.5m high (as shown in Figure 1), the collapse of the goaf caused the filling of the two gangs to rush into the goaf and the upper part of the upper ore body sink. The range of influence wave its neighbour six stopes, the N2-3# stope was located outside the slip line, and the instability collapse area had little effect on it, which could be mined according to the normal method, while the S1-2 stope belonged to the collapse area, therefore, mining it was a prerequisite to ensure safety during the stope. The mining scheme commonly used in the metal mine was a bottomless deep hole back-recovering and post-filling mining method. The method was characterized by high working efficiency and large amount of collapse, and the disadvantage was that the amount of primary detonation was large. Since the S1-2 stope was very high (55m), under the local geology permitted conditions, for the sake of safety, the mining sequence was bottom to top. And the bottomless deep-hole retraction type mining method was still used to mining the lower part of the 22m high ore body (the first mining stope in Figure 1).

3. Preliminary optimization method of mining sequence

Since there were still 8 stopes in the area of the collapsed area, there were many options for the mining sequence. Therefore, it was necessary to use the dynamic programming method to scientifically select each mining plan to achieve the optimal mining sequence plan.

(1) Mining optimization objective function and mining optimization weight function

The objective function of the optimization problem of the mining process in the area of the collapsed area should ensure the stability and safety of the surrounding rock to the utmost extent, that was: to the first i mining stage, the obtained mining optimization objective function value could be represented by \( F_i(x_i) \). It was indicated that the mining objective function increment caused by the mining of the i stage was called the mining optimization weight function \( P_i(x_i, y_i) \). Assume that in N step mining, the feasible solution to the mining sequence optimization problem was \( K \), and the solution space was \( S \), then there was \( K \in S \), and its expression was:
\[ \min f(K) = \sum_{j=1}^{Z} A_j(K) \]  

In the formula: \( A_j(K) \) was displacement value of the j stope (state variable); \( f(K) \) was Mining order optimization objective function; \( Z \) was total number of stopes in the collapsed area.

(2) Mining state transfer equation and mining optimization recursive equation

① mining state transfer equation was:

\[ x_{i+1} = x_i - y_i = m \quad (1, 2, \ldots, m) \]  

② mining optimization recursive equation was:

\[
\begin{cases}
F_0(x_0) = 0 \\
F_i(x_i) = \text{opt}_{y_i \in \mathbb{Z}(x_i)} \{ P_i(x_i, y_i) + F_{i+1}(x_{i+1}) \}
\end{cases}
\]  

The above was the dynamic programming mathematical model for the optimization of stope mining sequence in the unstable and collapsed area.

(3) Dynamic planning model implementation method

Using the dynamic programming mathematical model, taking mining displacement value as the objective function the target function in each stage, to analyze and compare displacement value in each mining stage. When the mining objective function value was the smallest, it was the optimal mining objective function.

The reason why mining and collapse occurred in the goaf was mainly because the mining caused the two-pack filling body in the goaf to lose its original supporting effect, so that the filling body was pushed into the goaf. After the collapse zone was formed, it was essential that determine the scientific and reasonable mining sequence of hidden danger resources to control the surrounding rock damage caused by stress redistribution during the process of adding and unloading, ensuring the stability of the roof and the two gangs, and that is seeking the best mining method for mining decision[8].

(4) Design of preliminary optimization plan for mining sequence

The resources of the unstable and collapsed areas must be exploited in a positive and prudent manner, and the possible mining sequences were determined as follows: Because the 0# stope was the most dangerous area, so under the current technical conditions of the mine, the grouting reinforcement treatment of the stope could not be realized, and the first mining 0# stope could be excluded, that was, the possible mining sequence was: the periphery of the slip surface was taken first, then the slip surface was taken at the edge, and finally the internal stop of the slip surface. In another case, mining was started from one end of the exit surface of the slip surface, and the other end was advanced step by step, that was, the possible mining sequence was the external stope to the north of the first mining slip surface, and then the internal stope of the slip surface, the slip surface edge of the stope, and finally the outer stope to the south of the slip surface; or the outer stope south of the slip plane, then the slip surface edge stop, the slip surface internal stope, and finally it was the external stope north of the slip surface. Identify the possible 10 mining sequence options (Figure 3):
Figure 3. Possible 10 mining sequence schemes

(5) Preliminary optimization of the objective function of the mining sequence
The purpose of searching the best optimization mining method was to obtain the best stability of the surrounding rock. Therefore, the mining objective function could be used as a criterion function to judge the pros and cons of each scheme [9]. Because of the complexity and uncertainty of the surrounding rock stability of the stope, the criterion of surrounding rock stability was mainly sought through the stop displacement index [10]. During the numerical simulation, the velocity field and the Displacement field were cleared, so the final displacement value was the value after the last step of excavation. Therefore, the optimization objective function could be expressed as.

\[ M \text{ in } f(D) = f(D_1) + f(D_2) + \cdots + f(D_n) \]  

(4)

In the formula: \( f(D_n) \) —— The displacement value formed by the nth step mining.

(6) Implementation of preliminary optimization of mining sequence
The specific preliminary optimization implementation method was as follows (Figure 4 was the optimization calculation flow chart): ① Parametric computational language programming was performed by FISH built in the numerical calculation model, and the optimized preliminary design file was saved as a .txt document and output. ② Selecting the memory search optimization algorithm in the dynamic programming algorithm, using MATLAB as a means to run the program to read the .txt file and optimize the file data. The specific optimization procedure was as follows. ③ Through the analysis and effect evaluation of the obtained results, and then further guide the optimization design (numerical analysis).

The objective function values in the 10 possible schemes were obtained by the above method (Table 1). The Displacement values in Scheme 1, Scheme 2, Scheme 6, and Scheme 10 were not much different. Due to the larger model, there may be a larger error in the calculation, therefore, the best optimization should also be determined by analyzing other mechanical response characteristics, that was, from the four feasible solutions, the optimal mining sequence was determined by numerical analysis, so that the determined scheme was not only feasible but also optimal.

Table 1. Dynamic optimization of target function values

|                | Program 1 | Program 2 | Program 3 | Program 4 | Program 5 |
|----------------|-----------|-----------|-----------|-----------|-----------|
| Displacement value /cm | 9.39      | 9.35      | 11.22     | 10.25     | 11.77     |
| Program 6       | Program 7 | Program 8 | Program 9 | Program 10|
| Displacement value /cm | 9.37      | 10.48     | 9.96      | 11.21     | 9.31      |
Table 2. Reverse order optimization scheme

|          | order 1 | order 2 | order 3 | order 4 | order 5 | order 6 |
|----------|---------|---------|---------|---------|---------|---------|
| Program a | N1-2#   | N0-1#   | 0#      | S0-1#   | S1# -1# | S1-2#   |
| Program b | S1-2#   | S1# -1# | S0-1#   | 0#      | N0-1#   | N1-2#   |
| Program c | N1-2#   | S1-2#   | N0-1#   | S1# -1# | S0-1#   | 0#      |
| Program d | S1-2#   | N1-2#   | S1# -1# | N0-1#   | S0-1#   | 0#      |

4. The optimization of final mining sequence numerical
The four mining sequences that are feasible were numerically optimized. The mechanical parameters in the numerical calculation were shown in Table 3 below.

Table 3. Rock mass mechanical parameters

| Name            | Elastic Modulus /kPa | Poisson's ratio | Volumetric weight/m³ | Cohesion /kPa | Internal friction angle /° | Tensile strength /kPa |
|-----------------|----------------------|-----------------|----------------------|---------------|----------------------------|-----------------------|
| Filling body 1  | 2750                 | 0.19            | 2.11                 | 0.74          | 38.0                       | 2.39                  |
| Ore body        | 19760                | 0.30            | 3.80                 | 2.45          | 40.3                       | 2.4                   |
| Filling body 2  | 2080                 | 0.21            | 2.23                 | 0.56          | 37.7                       | 1.96                  |

The minimum principal stress around the surrounding rock, the maximum displacement in the Z direction, and the volume of the plastic zone (Automatic calculation through FISH language programming built into digital software) were taken separately, and the optimization calculation of the mining sequence in the collapsed area was carried out, and the optimal mining sequence was obtained.

Table 4. Minimum principal stress of different mining schemes

| Mining plan | Minimum principal stress/(kPa) |
|-------------|-------------------------------|
| Program a   | N1-2# 0.40 N0-1# 0.48 N0-1# 0.42 S0-1# 0.30 S1# -1# 0.28 S1-2# 0.2 |
| Program b   | 0.38 0.43 0.52 0.38 0.59 0.3 |
| Program c   | 0.39 0.46 0.29 0.37 0.59 0.21 |
| Program d   | 0.40 0.41 0.31 0.39 0.48 0.25 |

Table 5. The Z direction of each mining scheme is the maximum displacement

| Mining plan | Maximum displacement in the Z direction/(cm) |
|-------------|-----------------------------------------------|
| Program a   | N1-2# 1.58 N0-1# 1.04 S0-1# 4.50 S1# -1# 1.05 S1-2# 0.80 |
| Program b   | 2.08 4.41 0.93 0.71 0.5 |
| Program c   | 1.49 4.82 0.95 0.71 0.6 |
| Program d   | 1.58 4.85 1.00 0.52 0.3 |

The data of the minimum principal stress, the z-direction maximum displacement, and the plastic zone failure volume of the four schemes were counted and compared (Fig. 5 to Fig. 7). It could be seen from the analysis results that the minimum principal stress of the four schemes was different, and the maximum displacement of the z-direction was not large. The minimum principal stress of both schemes b and c was greater than the tensile strength of the filler, so the schemes b and c were not selected. 0 #
Stope was a relatively dangerous stope, comparing the minimum principal stress of scheme a and d stop 0#, scheme d was smaller than scheme a, so scheme d was better than scheme a. It could also be seen from the comparison of the volume of the plastic zone that the scheme d was the optimized result. The displacement's change of the scheme d was the smallest, the stress concentration was the lowest, the plastic zone was the smallest, and the safety of the mining was the highest. Therefore, the option d was used to exploit the internal hidden resources and the resources at the edge of the slip surface of the collapse zone.

According to the numerical analysis optimization results, the S1-2# and N1-2# stop fields were at the edge of the collapsed area. The S1-2# stop was higher with a total of 7 segments. While mining the stope, the digging chamber could be arranged according to the detection condition of the drilling hole, and the grouting reinforcement treatment could be carried out according to the need to increase the stability of the S1# stope and even the S1#-1# stope. Therefore, mining from the S1-2# stop was the most reasonable. After comprehensive judgment, the optimal mining order of hidden danger stope was: from S1-2# to N1-2# and then S1#-1#. The next order is from N0-1# to S0-1# and 0#.

5. Conclusion
(1). According to the complicated mining technical conditions of the collapsed area and the distribution characteristics of the stope in the unstable hidden danger area, taking the displacement as the objective function, the preliminary optimal dynamic programming model of the mining sequence of the unstable collapse zone is established, and 4 feasible preliminary schemes were determined from the 10 schemes of possible mining sequence.

   (2). Using the numerical analysis method, the mining sequence optimization of the stope in the unstable collapse area is realized. According to the numerical analysis results, mining from the S1-2# stop is the most reasonable. After comprehensive judgment, the optimal mining order of hidden danger stope is: from S1-2# to N1-2# and then S1#-1#. The next order is from N0-1# to S0-1# and 0#.

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