Journal of Mineral Resources Engineering, 9(2): 33-45, (2024)

Imam Khomeini International University
Vol. 9, No. 2, Summer 2024, pp. 33-45

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering
(JMRE)

Research Paper

Optimizing Stope Boundary and the Undercut Level in Block Cave Mining

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Received: 31 Oct. 2021 **Accepted: 31 May 2022**

Abstract: As near-surface mineral resources are being depleted, mining operations are focused on deepening. Rising environmental concerns prefer underground mining methods because their footprint is less than that of surface mining methods. Among the underground mining methods, block caving is a method with low operating costs and comparable production rate to open-pit mines. Mine design and planning optimization is performed to ensure the optimal use of mineral resources with minimal possible extraction costs. Stope boundary optimization is vital in the underground mining planning process, and numerous algorithms have been proposed in that regard. The floating stope algorithm is the most widely used algorithm which is presented for those mining methods where selective mining is possible. This paper tries to apply the floating stope algorithm for stope boundary optimization in the case of block caving. In that regard, a framework is discussed to determine the input parameters of the floating stope algorithm that are suited for block caving including minimum block size, floating ranges, and cutoff grade. These parameters are defined to customize the floating stope algorithm for the block caving method. Then the customized algorithm is applied to optimize the boundary of the underground block caving stope. Then, the corresponding undercut level is determined using the "effective cross-section" heuristic. The procedure is applied in the Songun copper mine. Based on the results, the minable reserve is 617 million tons with an average copper grade of 0.53%.

Keywords: Block caving, Undercut level, Stope boundary optimization.

How to cite this article
Shami-Qalandari, M., Rahmanpour, M., and Mirabedi, S. M. M. (2024). *"Optimizing stope boundary and the undercut level in block cave mining"*. Journal of Mineral Resources Engineering, 9(2): 33-45.
DOI: 10.30479/JMRE.2022.16432.1557

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1- INTRODUCTION

With increasing depth and stripping ratio and transportation distance in open-pit mines, the operating costs in open-pit mining will increase. As a result, switching from open pit to underground mining may be more beneficial, or underground mining may be the only possible option for high overburden deposits. On the other hand, increasing environmental concerns have increased the tendency for underground mining [1]. In addition, managing high operating costs in underground mines is a significant challenge for mining companies. To meet the challenges associated with the high operating costs, mining companies have made efforts to reduce costs and increase efficiency. The block caving extraction method was developed in the late 19th century at the Menominee Ranges Iron Ore Mine in Michigan, USA. The Pewabic mine first used block caving, based on which other methods have been developed [2]. Block caving method is among the mass mining methods and the production costs are low and comparable to open-pit mining. Due to high productivity and the possibility of mechanization and labor costs reduction, the current tendency to this method is high in developed countries, and most open-pit mines (for example, Chuquicamata mine) are changing to the block caving method. Figure 1 shows a schematic view of the block caving method.

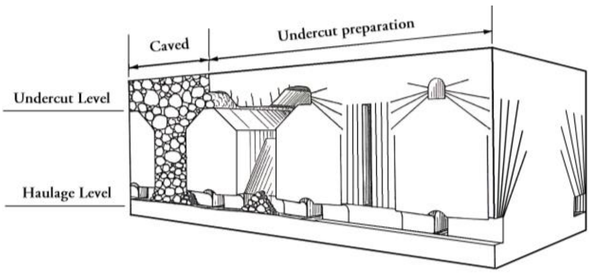

Figure 1. A schematic view of block caving method

Preliminary assessments of undercut level in block caving mines is an important issue that must consider various parameters such as extraction rate, block height, discount rate, block profit, extraction cost, and revenue [3]. PCBC (the short for Panel Caving/Block Caving) is commercial software that determines the boundary of block caving mine based on economic analysis [4,5].

The underground mine planning prob lem can be broken down into three sub-problems, including (1) Determination of stope layout or boundary, (2) Stope sequencing, and (3) Determination of access roads and networks. These sub-problems need to be optimized simultaneously. However, due to the size and complexity of the problem, it is not easy to optimize the three sub-problems simultaneously.

The stope layout optimization seeks to find a part of the mineral resources that maximize the mining profit. The first algorithm is proposed by [6] that is based on a dynamic programming model to optimize the stope boundary for the block caving mines. The octree division heuristic is proposed by [7]. In this method, when the resource model is determined, some geometric and economic constraints are applied to determine the mineable volumes. Then, the initial volume is divided into eight equal sub-volumes. The procedure continues until all sub-volumes are evaluated based on the containing ore and waste material. Finally, the combination of valuable sub-volumes is considered the optimal stope boundary. The floating stope algorithm is a search-based algorithm that determines the stope boundary of underground mines. It is a powerful tool for optimizing and sensitivity analysis of underground mineable reserves [8-12]. A heuristic algorithm called the Maximum Value Neighborhood (MVN) algorithm is proposed by [13] to optimize the stope boundary. This algorithm is somehow similar to the floating stope algorithm but applies a different approach to finding the optimal boundary. Apart from deterministic algorithms, some researchers are focused on uncertainty-based analysis. Some researchers have worked on a mixed-integer programming model to optimize stope design in uncertainty conditions [14]. Some proposed heuristics to find the stope boundary [15,16]. The proposed algorithm considers the mine block model and the related economic parameters. In this method, first, the economic block model is constructed. Then the optimal stope design is created by maximizing the total economic value according to the physical and geotechnical constraints. Matamoros and Kumral have proposed a method for efficient search of the feasible solution space for optimizing the stope design in the case of mineral uncertainty conditions [17]. Jalali et al. [18,19] presented an algorithm with mathematical logic called the OLPIS algorithm with the motive of simulating the technical and geometric characteristics of extraction stopes in different methods of underground extraction. Hou et al. [20] described an integrated optimization model for the simultaneous optimization of stope boundary and mine openings. In this model, the interdependence between stope and openers is considered by development cost. In this method, a model based on a mixed nonlinear programming model is proposed to maximize the overall economic value according to the existing constraints, and the genetic algorithm is used to solve the model. The case of stope boundary optimization in the case of sub-level stoping is studied by [21] using a multi-objective integer programming model. A hybrid algorithm that is a combination of dynamic programming and a greedy algorithm is presented by [22] to determine underground stope boundaries.

An underground stope is a production area in which rock is extracted using a suitable underground mining method. Defining the minimum dimensions of the stope according to physical and geotechnical constraints is essential [15]. The minimum dimensions of the stope are one of the main assumptions in almost all the underground stope boundary determination algorithms. Still, no article has been published that deals with determining the minimum stope dimensions in different underground mining methods. In this paper, the calculation of the minimum stope dimensions for the block caving method is investigated. Then, the calculated dimensions are used as the inputs of the floating stope algorithm to determine the stope boundary of block cave mining.

2- RESEARCH METHOD

Optimization of the block caving stope boundary requires a geological block model, a suitable optimization algorithm, and configuration of the algorithm according to the requirements of the mining method. Preparation of the geological block model and reserve estimation is the essential design step. After preparing the geologic block model, according to the geological, geomechanical, geometric, and economic parameters, the mining method is determined. Then the optimization algorithm is configured according to the selected mining method, and finally, with the implementation of the algorithm, the optimal stope boundary is defined. In the following, these steps are reviewed separately, and the details of each step are provided.

2-1- Resource modeling and grade estimation

Unlike classical statistics, geostatistics allows the calculation of estimation error. Therefore, it is possible to achieve error distribution. Geostatistical estimation of mineral reserves consists of two stages. The first step involves recognizing the spatial structure of ore grade and thickness. After spatial modeling of the deposit, block characteristics are estimated based on exploratory information and statistical and geostatistical studies. The continuity, homogeneity or heterogeneity, and spatial structure of the mineral reserve are examined by variogram. In the second stage, estimation is performed by the kriging method, which depends on the specifications of the fitted variogram model in the first stage. In this paper, indicator kriging has been used to model the estimation space. Then, simple linear kriging is implemented within the space, and ore grade is estimated.

Linear kriging is an interpolation function based on the variogram [23]. It is ideal to use a linear estimator when the data distribution is close to normal. Nonlinear kriging algorithms are a type of linear kriging based on a special nonlinear conversion of the original data [24,25]. Moreover, indicator kriging is a type of linear kriging. It is based on the nonlinear transformation of data by some threshold. Thresholds can be determined according to the cutoff grade. The basis of this method is that first, according to Equation 1, the variable is converted into binary values according to the given threshold.

$$i(u_\alpha : k) = \begin{cases} 1 & \text{if category } k \text{ is present at location } u_\alpha \\ 0 & \text{if not} \end{cases} \quad (1)$$

So each observation point u is assigned a value of 1 if it satisfies the threshold k, and otherwise a value of zero. The indicator variogram is obtained based on Equation 2.

$$\gamma_I(h) = \frac{1}{2} E\left\{\left[I(u;k) - I(u+h;k)\right]^2\right\} \tag{2}$$

Where:

$\gamma_I(h)$: the indicator variogram with lags of length h,

I(u; k): the indicator variable at the observation point u with respect to the threshold k,

I(u+h;k): is the indicator variable at the observation point u+h with the threshold k.

Estimation results can be obtained by one of the two simple and ordinary linear kriging methods. The ordinary kriging method determines the variable at a point based on the linear weight moving average according to Equation 3:

$$z^*(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \tag{3}$$

Where:

$z^*(x_0)$: the estimated value at the point x_0,

$z(x_i)$: the measured value of a point x_i ,

λ_i : the weight attributed to the variable at point x_i ,

n: is the total number of observations.

The aim is to obtain an unbiased estimate in which the mean difference between the estimated and measured values is zero (i.e.$\left[z^*(x_0) - z(x_i)\right] = 0$). Moreover, the sum of the weights should be equal to one. The kriging method also provides the best estimate by minimizing the kriging variance, so λ_i weights are obtained by solving Equations 4 and 5.

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{4}$$

$$\sum_{i=1}^{n} \lambda_i \gamma(x_i, x_j) + \mu = \gamma(x_0, x_j), j = 1, \ldots, n \tag{5}$$

Where:

$\gamma(x_i, x_j)$: the semivariogram,

μ: the Lagrange coefficient,

$\gamma(x_0, x_j)$: is the semivariogram between the points x_i and x_j .

2-2- Floating stope algorithm

In this paper, the Floating Stope algorithm is used to determine the optimal stope. The name “Floating Stope” is derived from floating a stope shape around a block to determine the optimal position of the stope with some specific conditions. This algorithm could be applied with respect to three different objective functions, including maximizing the tonnage of rock, metal content, or economic value of the extracted materials. The algorithm will produce two envelopes. The inner envelope is created by combining the best stope, and the outer envelope is obtained by the union of all possible stopes. The optimal stope boundary should be located as close as possible to the inner envelope and inside the outer envelope. Several parameters should be considered when locating the stope boundary between the two envelopes. These parameters are the characteristics of the extraction method, selective mining requirements, grade requirements, and ore grade and tonnage within the outer envelope.

An example of an inner and outer envelope in a two-dimensional model is shown in Figure 2. In this figure, the block size is 3×4 meters, the minimum stope size is 10×15 meters, and the floating range of stope is 5 meters. The inputs of this method include the minimum stope dimensions, stope floating range, cut-off grade, and head grade, which are calculated considering the dilution. Since this paper applies the floating stope method to optimize block caving stope layout, modifying the mentioned parameters based on the characteristics of the block caving method is necessary.

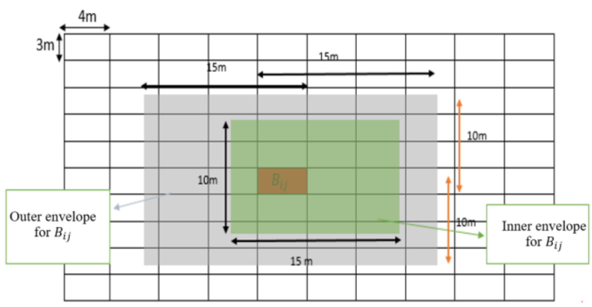

Figure 2. The inner and outer envelope for single block

2-3- Block caving configuration

The block caving method refers to a mass mining operation where the broken ore is extracted from the stope by the action of gravity. When a thin horizontal layer is removed from a predetermined mining level called undercut, the vertical support of the ore is removed. The remaining ore caves by gravity and is extracted through the mining level (Figure 1). As the extraction of broken ore continues, the ore continues to cave. Ideally, the ore and the surrounding rocks should be structurally weak enough to collapse. This method is capital-intensive and requires significant initial investment early in the mine life for infrastructure and initial development. High development costs are balanced by the high production rate and low operating costs over a considerable period. As a result, the total cost per ton of mined ore is lower than other underground mining methods.

2-3-1- Determining the undercut level

The block caving mines have three essential elements to be determined. These include the extraction system in the undercut level, the draw point design, and the extraction level. To locate these elements, one needs to determine the undercut level at first. In that regard, a heuristic method is introduced for the undercut level determination. In this method, the mineral deposit is divided into several levels. Then, by considering each level as an undercut level, the profit through the selected undercut level is calculated. Finally, the most profitable level is chosen as the suitable undercut level. The discounted profit of each block and each level are calculated using Equations 6 and 7, respectively:

$$v'_{nl}(x,y,z)=\frac{v_{nl(x,y,z)}}{(1+i)^{\frac{h}{v_{\min ing}}}} \tag{6}$$

$$p_l=\sum_{n=1}^{m} v'_{nl}(x,y,z) \tag{7}$$

Where:

$v_{nl}(x,y,z)$: the profit of block n and all its upper blocks in level l,

i: refers to discount rate, h is the block height,

v_{mining}: the vertical mining rate (m/year),

$v'_{nl}(x,y,z)$: the discounted profit,

p_l: is the discounted profit of level l.

Equations 8 to 10 are used to calculate the profit.

$$TR=g*T*R*(P-SC) \tag{8}$$

$$TC=T*(MC+PC) \tag{9}$$

$$PR=TR-TC \tag{10}$$

Where:

TR: stands for total revenue,

g: ore grade,

T: block tonnage,

R: stands for processing plant recovery,

P: the price,

SC: stands for selling cost,

TC, MC and PC: the total cost, mining cost, and processing costs respectively,

PR: is the profit of a block.

2-3-2- Determining the minimum stope dimensions

The minimum stope dimensions of the block caving method is an estimate of the cavability. Cavability refers to the transformation of intact rock into broken mass when undercutting [26], and it is estimated by some experimental and numerical methods. Experimental methods estimate rock mass cavability based on the undercut dimensions. Rock mass classification systems are commonly used in all experimental methods [27,28]. Forecasting rock mass cavability is one of the essential factors in the success of the block caving method. The strength of rock material and the strength and geometric properties of discontinuities are those characteristics that affect the cavability of the rock mass. Cavability of rock mass begins when the hydraulic radius of the undercut exceeds a critical value. Therefore, the minimum length and width of the stope can be equal to the minimum hydraulic radius required for rock mass destruction. The hydraulic radius is calculated using Equation 11.

$$R=\frac{A}{P} \tag{11}$$

Where:

R: the hydraulic radius,

A: the cross-section area,
P: is the perimeter of the area.

In the block caving method, blocks with high draw columns are desirable because the development cost is inversely related to the draw height. Of course, the design of a high draw column requires to drawing management to dilution control. Therefore, the minimum height of the stope can be considered equal to the height at which the mineral extracted can pay the cost of development and the minimum expected profit. In general, the minimum dimensions of the block caving stope depend on the cavability of the rock mass and the development costs.

Minimum stope dimensions are the most critical parameter of the floating stope algorithm. The experimental diagram of Laubscher caving is used to determine the minimum dimensions of the block caving stope. In the Laubscher caving diagram, a hydraulic radius is used to determine the cavability of the rock mass. The diagram in Figure 3 shows the caving and stable conditions in terms of hydraulic radius for a wide range of Mining Rock Mass Ratings (MRMR) and different underground space shapes. Accordingly, the higher the MRMR and the lower the hydraulic radius, the more stable the area. The diagram divides the space into three zones including a caving zone, a transitional zone, and a stable zone. This diagram is defined for rectangular stopes where one side is at least 1.5 times larger than the other (Diagram A) and for circular stopes with a specified diameter (Diagram B). Due to the fact that the general shape of block caving stopes is rectangular; and also this shape can be modeled by floating stope algorithm, thus, diagram A is used to determine the hydraulic radius and the rectangular stope dimensions considering the given MRMR. The minimum hydraulic radius that is required for the caving process to start is determined using the diagram A. Finally, the minimum stope dimension is calculated based on the minimum hydraulic radius.

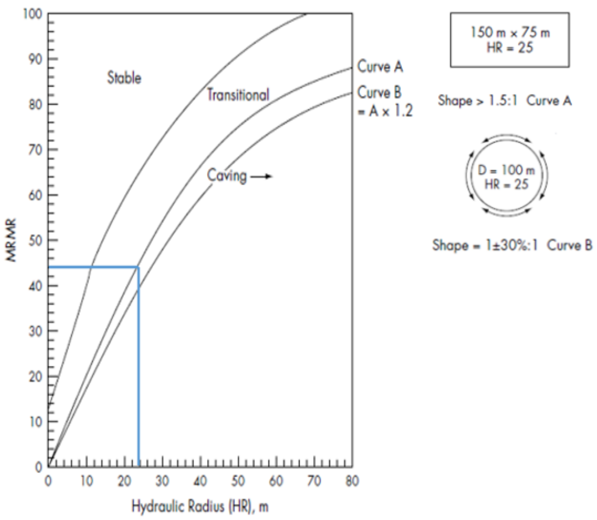

Figure 3. Laubscher caving diagram [Modified from 24]

2-3-3- Determining the minimum stope height

The minimum height of the stope is the height that can meet the costs related to the stope plus an expected profit. In that regard, a trial and error method has been used to calculate the minimum stope height. Therefore, the unit extraction costs are calculated, for which the O'hara cost estimation method [29] has been used. The net profit can be calculated by initially assuming that the total ore reserve will be extracted through one level. Then, by comparing the net profit and the minimum expected profit, it is possible to decide on the optimal stope height. If the calculated net profit is more than the minimum expected profit, then one level is added to the initial number of levels, and the calculations are repeated.

This process continues until the calculated net profit for a level is equal to the minimum expected profit. In this way, one could calculate the maximum number of development levels. If the total height of the ore reserve is divided by the maximum number of development levels, then one could calculate the minimum stope height.

2-3-4- Determining the Cut-off and head grade

Cut-off grade and the head grade are the other parameters required to determine the stope boundary layout. A mining cut-off grade is a grade that covers the costs of mineral extraction, processing, smelting, and refining. One could determine the mining cut-off grade by using Equation 12. The minimum head grade is determined according to the feed grade required by the processing plant.

$$g_c = \frac{c_m + c_h}{10(p - c_k)R} \tag{12}$$

Where:

g_c : the cut-off grade,

c_m : the mining cost,

c_h : the processing cost,

p: is the selling price of a kilogram of the final product,

c_k : the refining and selling costs per kilogram of final product,

R: is the total recovery.

The coefficient of 10 is used to convert the unit kilograms/ton into a percentage.

2-3-5- Determining the stope floating range

Another parameter required by the algorithm is the floating range of the minimum stope. The floating range is determined such that the centroid of the blocks corresponds to draw points, and this will facilitate grade control. The recommended distance between the draw points is shown in Figure 4. According to Figure 4, the distance between draw points is related to the drawing width, RMR, and caved rock size.

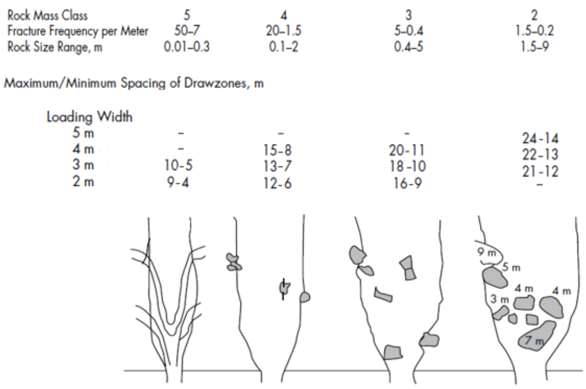

Figure 4. Recommended distance of draw points [Modified from 24]

3- CASE STUDY: SONGUN COPPER MINE

3-1- Resource modeling and grade estimation

Songun copper deposit is located in East Azerbaijan province, northwest Iran. This mine is located in a mountainous area with an average height of +2777 meters. The deposit is currently mined by open-pit mining. It should be noted that this study was carried out without considering the open pit section and assuming that the mine will be extracted totally using the block caving method.

Indicator Kriging (IK) is used to determine ore and waste blocks. Therefore, the estimation domain is defined so that it includes all the boreholes. According to studies, the Leach zone with an average grade of 0.1% has the lowest grade zone, the ore grade in the hypogene is 0.4%, and the supergene zone has an average grade of 0.62%. The mineralization zone is determined based on a cut-off grade of 0.2%. The data were processed and the indicator semivariogram is calculated. According to the calculations, the search ellipsoid diameter and orientation are determined, and a spherical model is used for IK (Table 1). A cross-validation procedure was used to find proper estimation parameters for IK (Table 2). Based on the results, the correlation coefficient is 0.98. The difference between the mean and variance of the original and estimated data was -0.0005 and 0.0130, respectively.

Table 1. Variogram models for ik

	Variance	Main direction	Sub-direction	Vertical direction
Nugget	0.026	-	-	-
Spherical 1	0.009	95	250	285
Spherical2	0.030	206	535	583
Spherical3	0.089	277	889	919

Table 2. Zone estimation parameters for ik

Parameter	Value	Parameter name	Value
X diameter	120m	Increase factor for the 2nd SE	1.2
Y diameter	80m	Increase factor for the 3rd SE	1.35
Z diameter	15m	Maximum number of used samples	25
Num. of ellipsoids	3	Minimum number of used samples	3

After defining the estimation zone by IK, copper grade variography is calculated. The copper grade distribution is shown in Figure 5. Then, the search ellipsoid diameter and orientation are determined, and a spherical variogram model is fitted. The specification of the variogram model, cross-validation results, and the estimation parameters are listed in Tables 3 and 4.

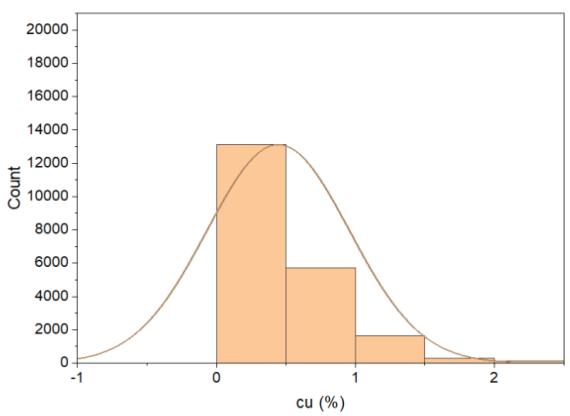

Figure 5. Distribution of copper grade data for Songun copper mine

Table 3. Specification of variogram model for cu grade estimation

	Variance	Main direction	Sub-direction	Vertical direction
Nugget	0.035	-	-	-
Spherical 1	0.053	123	138	142
Spherical2	0.063	275	310	378
Spherical3	0.084	434	602	667

Table 4. Cross-validation results and copper grade estimation parameters

Parameter	Value	Parameter	Value
Ave. grade of samples	0.4	Correlation coefficient	0.85
Estimated Ave. grade	0.4	Number of estimated samples	21802
Sample variance	0.22	Number of not estimated samples	3913
Estimated variance	0.15	Increase factor for the 2nd SE	1.2
X diameter	567m	Increase factor for the 3rd SE	1.35
Y diameter	500m	Maximum number of used samples	25
Z diameter	280m	Minimum number of used samples	3

The geological block model is generated according to the distance of exploratory boreholes. The block model contains 299’040 blocks of size 12.5×25×25 meters. IK method was used to estimate ore and waste boundaries. Then block estimation process was performed based on the parameters mentioned earlier, and the corresponding grade-tonnage curve is shown in Figure 6. The estimated mineral resource is about 1400 Mt.

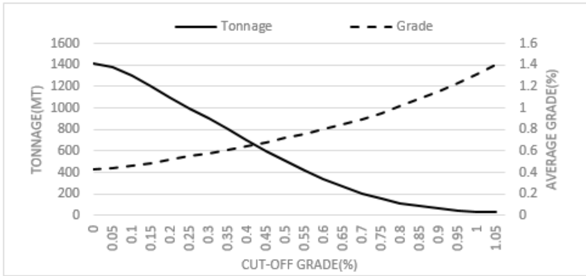

Figure 6. Tonnage-grade diagram

3-2- Stope boundary optimization

3-2-1- Parameter customization

Before applying the floating stope algorithm, the required parameters of the algorithm must be determined. According to geotechnical studies [30], the average MRMR is 43. Considering MRMR=43 and the Laubscher caving diagram (Figure 3), the minimum hydraulic radius is 23 meters. Therefore, to achieve a stope with a hydraulic radius of 23, a stope with an area of 9.8 thousand square meters should be designed. Thus, a 140×70 stope must be created. The largest dimension of the stope is deemed to be parallel to the largest diameter of the search ellipsoid.

The minimum height of the stope is the height that can meet the costs associated with the stope plus a minimum expected profit, which is determined by the trial and error method. The unit costs estimated using the O’hara method are reported in Table 5. According to the calculations, the maximum number of development levels for the Songun copper mine was nine. Since the height of the mineral zone (the highest level is 2340 and the lowest level is 1420 meters) is 900 meters, so the minimum stope height for this mine is 100 meters. Figure 6 shows a schematic view of the recommended minimum dimensions of the block caving stope. By considering the economic parameters given in Table 5, the mining cut-off grade is 0.2%. Also, the minimum head grade of the stope is 0.4%, according to plant feed grade.

Table 5. Cost estimation results

Parameter	Value	Parameter	Value
Extraction and development costs	1.9 \$/ton	Total recovery	85 %
Processing cost	6.3 \$/ton	Cost of smelting and refining	430 \$/ton cu
Capital cost	1.4 \$/ton	Copper prices	6000 \$/ton cu
Overhead cost	0.45 \$/ton	Minimum expected profit	400 M\$

Considering Figure 4 and the MRMR, the optimal distance of draw points is 17.5 m. Therefore, the length and width of the stope are divided into 8 and 4 sub-blocks, respectively (Figure 7). This will cause draw points to be located in the center of each sub-block to facilitate caving management and grade control. A summary of the parameters required by the floating stope algorithm is given in Table 6.

3-2-2- Determining the optimal stope boundary

After determining the required parameters, the floating stope algorithm was implemented to determine the stope boundary. One should note that the stope boundary is defined without considering the possibility of an open-pit option.

After running the algorithm, the inner and outer envelopes are determined. Figure 8 shows the inner and outer envelopes created by the floating stope algorithm. These envelopes will guide the designer to locate the stope boundary.

The optimal boundary should be as close as possible to the inner envelope and inside the outer envelope. The characteristics of both envelopes are given in Table 7. According to this table, the ore grade in the inner envelope is higher than the grade in the outer envelope. Considering ore grade and tonnage in the outer envelope, one could infer

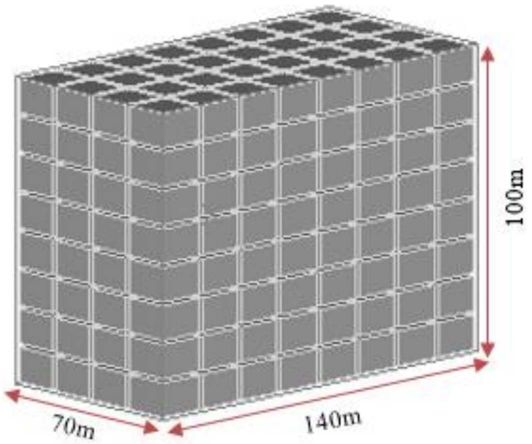

Figure 7. View of the minimum dimensions of the stope

Table 6. Customized Parameters for the algorithm

Parameter	Value	Parameter	Value
Cut-off grade	0.2%	Objective function	Maximize grade
Head grade	0.4%	Block dimensions	17.5×17.5 ×12.5
Min. stope dimensions in X axis	70 m	Floating range in X	4 blocks
Min. stope dimensions in Y axis	140 m	Floating range in Y	8 blocks
Min. stope dimensions in Z axis	100 m	Floating range in Z	8 blocks

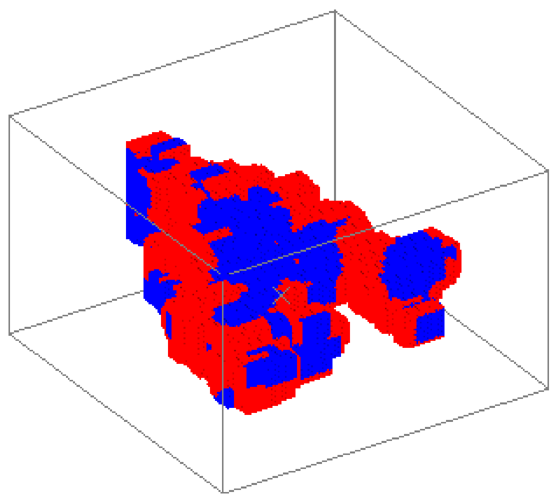

Figure 8. A view of the inner (blue) and the outer envelope (red)

that mining the outer envelope does not change the average grade of the mineable reserve. Moreover, because the ore grade in the outer envelope is higher than the cut-off grade, and due to lack of selectivity in the block caving method, the outer envelope can be selected as the stope boundary.

Table 7. Tonnage-grade of the inner and outer envelopes

Parameter	Tonnage (Mt)	Grade (%)
Inner envelope	688	0.6
Outer envelope	244	0.29
Both envelopes	932	0.52

Evaluation of the stope boundary shows that the expansion of the stope boundary is not the same at different levels. Therefore, the cross-section heuristic has been used to determine the proper stope boundary. The cross-section heuristic will determine the most suitable level for locating the undercut level. The data required to perform the cross-section analysis is provided in Table 5. According to this information, the boundary obtained from the floating stope algorithm was divided into 59 levels. Then the profit and the ore tonnage were obtained according to (6) to (10). Figure 9 shows a summary of the calculation results. According to the results, the elevation of 1687.5m was selected as the undercut level because this level has the highest NPV compared to other levels. Due to the mountainous topography of the region, some part of the reserve has a height of 900m. Moreover, its division into several levels will increase the development costs. According to [31-33] a cave height of about 1,200 meters has been practiced in block caving projects. Therefore, the whole deposit is designed to be mined via a single undercut level. A 3D view of the undercut level and the optimized stope boundary is shown in Figure 10. According to the selected undercut level, the mineable reserve is 617 Mt with an average grade of 0.53%. Also, the footprint of the required development area is 92 hectares.

4- RESULTS AND DISCUSSIONS

As near-surface mineral resources are being depleted, mining operations are focused on deepening. Among the underground mining methods, the block caving method is competitive in terms of production rate and costs with open-pit mines. Underground mine planning can be broken down into three sub-problems: (a) determination of stope layout, (b) stope sequencing, and (c) determination of development network. For complete optimization, these sub-problems must be solved simultaneously. However, the current computational resources do not allow the simultaneous optimization of the three sub-problems due to the size and complexity of the problem. Therefore, the first step is to determine the boundary of the underground stope layout. Among the algorithms presented for optimizing the stope boundary, the floating stope heuristic is widely used.

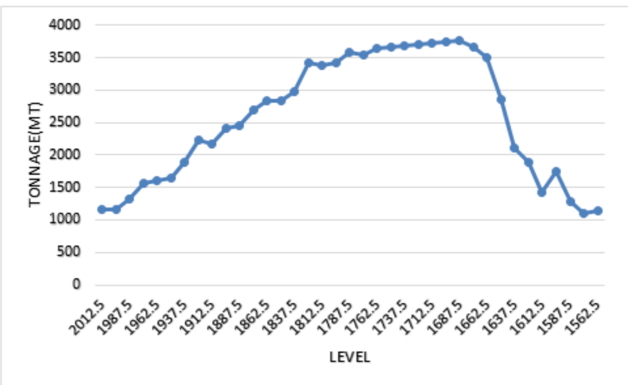

Figure 9. Tonnage - NPV diagram of different undercut levels

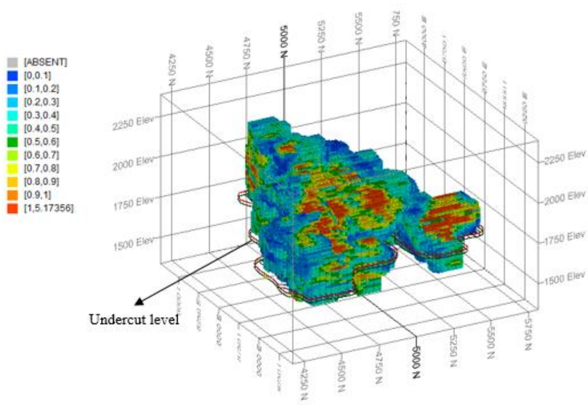

Figure 10. The location of the undercut level compared to the boundary determined by the floating stope algorithm

This paper presents the application of the floating stope algorithm to determine the stope boundary of a block caving operation. The algorithm is applied in the Songun copper mine. Some parameters need to be specified before using the algorithm, and they should be modified concerning the selected mining method. This paper presents the procedure of determining the minimum dimensions of the block caving stope. It is shown that the minimum dimensions of the block caving stope depend on the minimum hydraulic radius required for caving, extraction costs, and the expected profit. According to the calculations, the minimum stope dimensions for the Songun mine is 100×140×70 meters. Since the expansions of the stope boundary are different at successive levels, then the boundary should be modified such that it fits the requirements of the block caving method. The block caving method is not selective, so the proper stope boundary is determined using the cross-section heuristic. Based on the results, the mineable reserve is about 617 million tons with an average grade of 0.53%.

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نشریه مهندسی منابع معدنی، سال ۱۴۰۳، دوره نهم، شماره ۲، ص ۴۵-۳۳

نشریه مهندسی منابع معدنی
Journal of Mineral Resources Engineering
(JMRE)

دوره نهم، شماره ۲، تابستان ۱٤۰۳، صفحه ۳۳ تا ٤۵
Vol. 9, No. 2, Summer 2024, pp. 33-45

علمی-پژوهشی

بهینه‌سازی محدوده کارگاه و طبقه زیربرش در روش استخراج تخریب بلوکی

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دریافت: ١٤٠٠/٠٨/٠٩ پذیرش: ١٤٠١/٠٣/١٠

چکیده

با اتمام منابع معدنی در نزدیکی سطح زمین، عملیات معدنکاری در اعماق مورد توجه قرار می‌گیرد. نگرانی‌های محیط زیستی در مورد معدنکاری زیرزمینی کمتر از روش‌های استخراج سطحی است، زیرا ردپای معدنکاری زیرزمینی معمولا کمتر از معادن سطحی است. در بین روش‌های استخراج معادن زیرزمینی، روش تخریب بلوکی از نظر نرخ تولید و هزینه‌های تولید قابل مقایسه با روش روباز است. هدف از طراحی و بهینه‌سازی برنامه تولید استفاده بهینه از منابع با کمترین هزینه استخراج است. تعیین محدوده کارگاه در روش‌های زیرزمینی امری ضروری است و الگوریتم‌های متعددی در این خصوص ارایه شده است. الگوریتم کارگاه شناور از پرکاربردترین آنها به شمار می‌رود. این مقاله سعی دارد تا از الگوریتم کارگاه شناور برای تعیین محدوده کارگاه تخریب بلوکی استفاده کند. از این رو، چارچوبی برای تعیین پارامترهای مورد نیاز این الگوریتم متناسب با محدودیت‌های تخریب بلوکی ارایه شده است که شامل حداقل ابعاد کارگاه، نرخ شناوری کارگاه و عیار حد است. این پارامترها به نحوی تعریف شده‌اند که ملزومات روش استخراج تخریب بلوکی را برآورده می‌سازند. پس از اصلاح پارامترهای ورودی، این الگوریتم برای انتخاب محدوده کارگاه در روش استخراج تخریب بلوکی به کار رفته است، سپس از روش ابتکاری مقطع موثر برای تعیین موقعیت طبقه زیربرش استفاده شده است. این روش بر اساس اطلاعات معدن مس سونگون اجرا شده است. طبق نتایج، مقدار ذخیره قابل استخراج در حدود ۶۱۷ میلیون تن با متوسط عیار ۰٫۵۳ درصد محاسبه شده است.

کلمات کلیدی

تخریب بلوکی، طبقه زیربرش، بهینه‌سازی محدوده کارگاه.

استناد به این مقاله

شامی قلندری، م.، رحمانپور، م.، میرعابدی، س. م. م.؛ ۱۴۰۳؛ "**بهینه‌سازی محدوده کارگاه و طبقه زیربرش در روش استخراج تخریب بلوکی**". نشریه مهندسی منابع معدنی، دوره نهم، شماره ۲، ص ۴۵-۳۳.

DOI: 10.30479/JMRE.2022.16432.1557

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