Research of Optimal Transition Depth in opencast-underground combined mining

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Abstract. It will be of great significance to the accurate evaluation of the deposit’s economic potential and the improvement of economic performance and production capacity for mining enterprise, if the border was considered scientifically. Open-pit limit was optimized by mining software on the basis of combined mining cost analysis. The principal of combined mining transition depth determination was confirmed through the comparison of open-pit mining and underground mining costs. This paper will provide a reference for the practical application of combined mining transition depth determination.

1. Introduction
As open pit mines are exploited deeply, more and more examples of open pit and underground combined metal mines appear. Restricted by the shape of deposit or other factors, some ores locate deep and wings of the deposit would be wasted. Therefore, in the 1970s, Soviet scientists proposed combined mining method to solve this problem. Combined mining is applying two mining technology in only one deposit. The aim is comprehensive utilization of mineral resources and the descent of costs [1]. Combined mining method is usually applied to deposits that extend largely underground. The upper part of the ore body is exploited by open-pit method, as well as the deeper part is mined by underground method [2]. In the design of combined mining, the determination of transition depth is of great significance to ensure the economic benefits of the mine. A polymetallic mine is the engineering background of this research. The way to determine the transition depth of combined mining method will be obtained by economic model of both open-pit and underground method according to the principle of economic benefit maximization.

2. The economical parameter model of combined mining
The boundary optimization of combined mining is to determine the boundaries of opencast mining segment, underground mining segment and non-mining segment of a particular mine. From an economic point of view, the boundary optimization of combined mining is to delineate the marginal surface of mining deposit to maximize the economic benefits.

Through different price parameters, the first step is to access a series of nested optimization limits by mining software, which is based on the grade of ore body, combined with the cost of production of minerals, ore prices, space constraints and technical parameters, then optimized by computer program to obtain maximum economic benefits realm of open-pit mining[3]. Then the realm between two adjacent multi-mined can be calculated after becoming the concentrate production cost of the product, shown as figure 1, abcd and a’b’c’d’ were two realm pits, where the bottom depth of abcd realm was deeper than a’b’c’d’.
When calculating the total cost of production between the two realm ore, open pit mine need to calculate the cost of mining ore beneficiation costs, administrative expenses, selling expenses, processing costs and the stripping costs of rocks. Therefore, the unit cost of production of minerals within the different realm is calculated as equation 1.

\[ C = \frac{C_y + C_r}{M_k} \]  

Where: \( C \) is mineral production cost per ton, yuan/t; \( C_k \) is mining, processing, management, total cost of sales, yuan; \( C_y \) is rock stripping, total cost management, yuan; \( M_k \) is the difference between the total amount of ore realm, t.

![Figure 1. Sketch of ore and rock between two open-pit limit](image)

Equation 1 can be drawn a total production cost of ore mined from a deeper realm. Since the underground mining method does not require the calculation of the stripping costs, therefore only need to consider the production cost of this part of mineral. The impact of the stripping rock volume for the cost of production within the limit had a great relationship with the useful mineral distribution. When the ore body was buried deeply, the initial state of open-pit mining would have a greater mining cost.

3. Research of transition depth optimization method

3.1 Comparative analysis of cost curves

According to the analysis of open-pit mining costs, the change trend of cost per ton ore with depth was shown in Fig.2 Curve l. \( C_0 \), the lowest point of cost per ton ore, was determined by main access and stripping rock volume. Cost per ton ore beside the point of \( C_0 \) was roughly upwards trend. \( H_m \), the corresponding depth of \( C_m \), indicated the bottom depth of the biggest open-pit limit under the current price conditions. Change trend of cost per ton ore with underground mining method was shown in Fig.2 Curve d.

\( C_x \) was the cost intersection of open-pit method and underground method. \( H_x \), the depth of \( C_x \), was economical reasonable transition depth of open-pit and underground combined mining method. When the price came down, the case of \( H_m \) lower than \( H_x \) would emerge. In this case, the exploitation should stop when the open-pit limit fell to a certain depth. Otherwise, or it would cause the loss of mining enterprises. At the same time, because of the ore price limit, the value of deposit was not enough to apply underground mining method. In this situation, if the grade distribution was average in this deposit, the combined mining method was not suitable for the deposit. Single open pit mining method with a limit of \( H_m \) should be applied in this deposit. The other ores could not be mined recently. If the lower part of the deposit was richer than the upper part, ores buried deep could be exploited by underground mining method economically. The depth of open pit was \( H_m \).
3.2 Approach to determine the boundary of combined mining method

According to the above analysis, the approach to determine the reasonable boundary is determined as follows:

(1) Through the data of open pit mining cost and the open pit Nested with each other, the volume of rocks and ores between two limits could be determined. The cost of per ton ore could be calculated with equation 1 and the depth should be recorded. Then the change trend of cost per ton ore with depth could be determined. The maximum open pit limit could be obtained according to the principle of open pit limit determination.

(2) The underground mining cost was computed from the technical parameters of the method. The cut-off grade of underground mining could be calculated from the date of exploiting cost and then the range of underground mining.

(3) If the intersection of underground mining range and the open pit exists, the depth where cost of underground mining and open pit mining were equal should be found. If this depth was higher than the maximum open pit, it was the transition depth of combined mining method. Ores above this depth should be mined by open pit mining method, while the below should be exploited by underground mining method. If the transition depth was lower than the maximum open pit, the open pit of combined mining method was the maximum pit. Then the range of underground mining method should be schemed by the cut-off grade.

4. Case study

This research took a polymetallic mine as engineering background. The principle above was applied to the transition depth optimization of this mine. The ore type of this deposit could mainly divide into two types: skarn and hornfels. The grade distribution of this deposit was described as the upper part poorer and the lower part richer. The economical parameter should be determined at first. Through analysis of open pit depth and cost data of a number of large and medium-sized mines combined with the actual situation of this mine, the relation coefficient of transition cost per ton ore incensement and mining depth was 0.03 yuan/m[4]. Therefore, the cost of open pit mining was $116.24+0.03H$ yuan/t and the stripping cost was $13.82+0.03H$ yuan/t. A serious of nested limits, based on geological model of the deposit, was resulted from computer software, as shown in Fig.3. The price parameter adjustments were 80%, 90%, 100%, 110% and 120% [5].
Figure 3. Section view of the nested limits according to prices adjustment

Assuming the price of each metal change in same proportion, ore quantity, rock quantity, stripping cost, mining cost and net value in the nested limits determined by each price adjustment were shown in table.1.

Table1. The amount of ore and rocks and costs under the price changes

| Price Level (%) | Depth (m) | Ore Quantity (Mt) | Rock Quantity (Mt) | Mining Cost (Myuan) | Stripping Cost (Myuan) | Total Cost (Myuan) | Net Value (Myuan) |
|-----------------|-----------|-------------------|-------------------|--------------------|-----------------------|-------------------|------------------|
| 80              | 4650      | 249.11            | 87.62             | 28431.98           | 42538.91              | 32685.87          | 11251.31         |
| 90              | 4577.5    | 352.69            | 127.25            | 40212.01           | 5793.78               | 46005.79          | 13565.48         |
| 100             | 4530      | 466.42            | 194.56            | 53198.28           | 8309.04               | 61507.32          | 14448.22         |
| 110             | 4487.5    | 567.77            | 250.18            | 64847.14           | 10353.67              | 75200.80          | 14044.69         |
| 120             | 4432.5    | 637.78            | 300.08            | 72954.25           | 12254.41              | 85208.66          | 12896.29         |

The average cost between two adjacent pit was calculated from table.1 and equation.1, as shown in table.2.

Table2. The amount of ore and rocks and costs between two limits

| Price Level(%) | Ore Quantity(Mt) | Rock Quantity(Mt) | Production Cost (Myuan) | Average Cost (yuan/t) |
|----------------|------------------|-------------------|-------------------------|-----------------------|
| 80             | 103.58           | 39.63             | 13319.92                | 128.599               |
| 90             | 113.74           | 67.31             | 15501.53                | 136.293               |
| 100            | 101.35           | 55.62             | 13693.49                | 135.118               |
| 110            | 117.94           | 87.15             | 16965.60                | 143.886               |
| 120            | 47.90            | 37.25             | 6957.74                 | 145.268               |

The open-pit mine cost was shown in Fig 4, where the trend of the open pit mining production cost was first decreasing then rising with the change in the depth of exploitation, the reason was that the cost of open pit mining and ore production was closely related to the occurrence of underground mine. According to the results in Fig 2, the depth of Hx was larger than the depth of Hm, which indicated that the final bottom elevation of the open pit mine should be the elevation of D, but the ore was still have economic benefits under the open pit mine, which was available for underground mining. Therefore, the boundary of the combined mining was the low grade ore between the maximum open pit limit and underground mining range.
5. Conclusions

Through the analysis above, conclusions were drawn as below:

(1) The combined mining economic parameters have been determined through the cost analysis of open-pit and underground mining, providing the references for the reasonable cost parameters for boundaries determination.

(2) Ore block model and pit optimization results were made by using mining software, which offered the basis for boundaries determination of combined mining.

(3) Boundaries of combined mining are affected by economic factors. Comparison of open-pit and underground mining cost, as well as consideration of deposit conditions and technical conditions are necessary. The given principles in this paper are proved feasible by an example study in a metal mine.

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