PRINCIPLES FOR OPTIMUM DESIGN OF OPEN PIT MINES①

Shi Zhongmin, Feng Zhongren, Xu Changyou
Department of Mineral Resource and Environment Engineering, Wuhan University of Technology, Wuhan 430070
Zhang Youdi
Department of Mining Engineering, China University of Mining and Technology, Xuzhou 221008

ABSTRACT In 1965 Lerchs and Grossman presented the famous graph theory method for determining the optimum ultimate open pit limits. Since then many such numerical methods have been reported one after another in the literature concerned. Based on those methods, the principles for the optimum design of the open pit limits have been demonstrated in this paper. Upon these principles an optimum criterion to design the open pit limits was established to evaluate, improve and apply the present numerical methods, also to study and approach the new ones.

Key words open pit limit optimum design numerical method design criterion basic principle

1 INTRODUCTION

Now there are two prevailing ways to classify the various design methods of the open pit limits, which are the manual methods and the computer methods based upon the calculating means, and the rigorous algorithms and the heuristic algorithms based upon the calculating precision[1,2]. With the calculating principles, these methods can also be classified. This classification can not only evaluate the operation efficiency and development prospects of the design methods by itself, but also demonstrate their technical characters and improving avenues in theory.

A concept system, which was established with the help of set theory, can give a common description and abstract generality for the principles of the design methods such as the graph theory method[3]. These principles give a sufficient and necessary condition for an optimum open pit limit. The condition can be used as a criterion to examine the optimum open pit limits, also as a standard to judge such design methods.

2 CONCEPT SYSTEM

Without loss in generality, taking the two dimensional case for example (see Fig. 1), a concept system for describing the optimum design of open pit limits is established as follows.

i ↓ / j →	1	2	3	4	5	6	7	8	9
1	0	−1	−1	1	0	−1	−1	−1	−1
2		0	−1	−1	1	−1	−1	0	
3			3	2	1	2	3		
4				−1	3	−1			
5					1				

Fig. 1 Two dimensional ore body model

(1) Block and its mass

A basic unit volume mined in the pit is called a block, which is marked b_{ij} (see the square in Fig. 1). Every block b_{ij} is given a real

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number $m(b_{ij})$ as its mass (see the number in the square in Fig. 1), such as $m(b_{35})=1$. The mass of a block is an abstract title, which may have relevant economic meanings in various cases, such as the net value of the block for its one meaning, which is the difference between the value of the ore contained in the block and the cost for extracting it.

(2) Supporting structure and supporting set

For the blocks there exists a restrain relation to mine them. The relation is called supporting structure among the blocks, which corresponds to the slope structure of an open pit limit. The supporting structure can be described by a supporting model or a supporting pattern of the blocks[4, 5]. Upon the supporting structure, a block set $\Gamma(b_{ij})$ can be defined for any block b_{ij} and is called the supporting set of the block b_{ij}, which represents the blocks to directly cover b_{ij}. For the simplest case, it is assumed that the block is a cube and the maximum slope angle is 45° in all areas and directions of the mine, then the supporting sets of any block b_{ij}, except for those in the first low, consist of three blocks, namely, $\Gamma(b_{ij})=\{b_{i-1,m} ☞ i\neq 1, m=j-1, j, j+1\}$.

(3) Ore body model

There exist sets $B=\{b_{ij}\}$, $M=\{m(b_{ij})\}$ and $A=\{\Gamma(b_{ij})\}$. Three systems, which consist of the sets above, (B), (B, M) and (B, M, A) are called a block model, an economic model and a mining model of the ore body, respectively.

(4) Closure

In the system (B, M, A), a closure is a set of blocks C_s, that is, if a block belongs to C_s then this block' s supporting set must also belongs to C_s, In other words, if $b_{ij}\in C_s$, then $\Gamma(b_{ij})\subset C_s$. A closure represents a feasible open pit limit. If $C_s=\Phi$, then it is called an empty closure and marked C_Φ. All of the following block sets are the closures, $C_1=\{b_{14}, b_{15}, b_{16}, b_{25}\}$, $C_2=C_1\cup\{b_{12}, b_{13}, b_{23}, b_{24}, b_{34}\}$, $C_3=C_1\cup\{b_{11}, b_{12}, b_{13}, b_{22}, b_{23}, b_{24}, b_{33}\}$, $C_4=C_3\cup\{b_{17}, b_{18}, b_{26}, b_{27}, b_{34}, b_{35}, b_{36}, b_{45}\}$, $C_5=C_4\cup\{b_{19}, b_{28}, b_{37}\}$ and $C_6=C_5\cup\{b_{44}, b_{46}, b_{55}\}$. There exist two closures C_r and C_s, if $C_r\subseteq C_s$ or $C_r\subset C_s$, then C_r is the subclosure or the real subclosure of C_s, such as $C_1\subset C_2$ and $C_1\subset C_3\subset C_4\subset C_5\subset C_6$.

(5) Mass of closure

The mass $m(C_s)$ of a closure C_s is the sum of the mass of the total blocks belonging to C_s, namely $m(C_s)=\sum_{b_{ij}\in C_s} m(b_{ij})$, such as $m(C_1)=1$, $m(C_2)=-1$, $m(C_3)=0$, $m(C_4)=4$, $m(C_5)=6$ and $m(C_6)=5$. Obviously, $m(C_\Phi)=0$.

(6) Profitable and lossy closure

If $m(C_s)\geqslant 0$, then C_s is called a profitable closure, otherwise a lossy closure. If $m(C_s)>0$, then a real profitable one. Among the 6 closures above, C_2 is a lossy closure, C_3 is a profitable one and the other real profitable ones.

(7) Strong closure

Assuming C_r is any subclosure of the profitable closure C_s, if $m(C_r)\leqslant m(C_s)$, then C_s is called a strong closure, which is equal to an optimum open pit limit in some stages. C_1, C_4 and C_5 are strong closures, also the empty closure C_Φ is a strong one.

(8) Maximum closure

In the system (B, M, A), a closure with maximum mass is called a maximum closure, which is an optimum limit of the open pit, such as C_5 being a maximum closure.

(9) Increment-closure

An increment set between a closure C_s and its subclosure C_r defines an increment-closure, noted as $I_{s.r}=C_s\setminus C_r$, which is called the increment-closure of C_r (for C_s). For example, $I_{2.1}$, $I_{3.1}$, $I_{5.4}$, $I_{6.4}$ and $I_{6.5}$ are all increment-closures. Any closure can be regarded as an increment-closure of the empty closure, namely, $C_s=I_{s.\Phi}$, so a closure is a kind of special form of an increment-closure.

Similar to some concepts about the closure, following concepts such as mass of an increment-closure $m(I_{s.r})$, subaltern, profitable, strong and empty increment-closure can be defined.

(10) Common compensation between increment-closures

There exist two lossy increment-closures $I_{s.r}$ and $I_{t.r}$, namely $m(I_{s.r})<0$ and $m(I_{t.r})$

< 0, and $I_{s.r} \cap I_{t.r} \neq \Phi$. Noted as $I_{s \cup t.r} = I_{s.r} \cup I_{t.r}$, if $m(I_{s \cup t.r}) \geqslant 0$, then there is a common compensation between $I_{s.r}$ and $I_{t.r}$, $I_{s \cup t.r}$ is called a common compensation increment-closure. For example, $m(I_{2.1}) = -2$, $(I_{3.1}) = -1$ and $m(I_{2 \cup 3.1}) = 1$, so that , $I_{2 \cup 3.1}$ is a common compensation increment-closure.

(11) Help compensation between increment-closures

For a profitable increment-closures $I_{t.r}$, i.e., $m(I_{t.r}) \geqslant 0$, if there is a division $I_{t.s}$ and $I_{s.r}$ of $I_{t.r}$, namely $I_{t.s} \cup I_{s.r} = I_{t.r}$ and $I_{t.s} \cap I_{s.r} = \Phi$, and $m(I_{t.s}) < 0$, $m(I_{s.r}) > 0$, then there is a help compensation between $I_{t.s}$ and $I_{s.r}$, and $I_{t.r}$ is called a help compensation increment-closure. For example, $m(I_{6.4}) = 1$ and $m(I_{6.5}) = -1$, $m(I_{5.4}) = 2$, so that $I_{6.4}$ is a help compensation increment-closure.

3 FUNDAMENTAL THEOREMS

Theorem 1: If there exist a strong closure C_r and its strong increment-closure $I_{t.r}$, then the closure $C_t = C_r \cup I_{t.r}$ is also a strong closure.

Proof: Any subclosure of C_t can be expressed as $C_s = (C_s \cap C_r) + (C_s \setminus C_r)$, due to $(C_s \cap C_r) \subseteq C_r$ and $(C_s \setminus C_r) \subseteq I_{t.r}$, then $m(C_s) = m(C_s \cap C_r) + m(C_s \setminus C_r) \leqslant m(C_r) + m(I_{t.r}) = m(C_t)$, so that C_t is a strong closure.

This completes the proof.

Theorem 2: In a profitable increment-closure $I_{t.r}$, there must be one of its sub-increment-closures, which is a strong increment-closure.

Proof: If $I_{t.r}$ is not a help compensation increment-closure, then $I_{t.r}$ is a strong increment-closure in itself, otherwise $I_{t.r}$ has a real sub-increment-closure $I_{s.r}$ which is a profitable increment-closure. Repeating this process for $I_{s.r}$, a strong increment-closure, which is a real sub-increment-closure of $I_{t.r}$, must be found. This completes the proof.

Because the closure is a special form of the increment-closure, an inference of theorem 2 can be obtained.

Inference 1: In a profitable closure, there must be one of its subclosures, which is a strong closure.

Theorem 3: The sufficient and necessary condition for a strong closure C_s being a maximum one is that there does not exist any strong increment-closure $I_{t.s}$ of C_s, which is not empty.

Necessity proof: Assuming that C_s is a maximum closure, if there exists a strong increment-closure $I_{t.s}$ of C_s, from theorem 1, there must be a strong closure $C_t = C_s \cup I_{t.s}$, and $m(C_s) \leqslant m(C_t)$, which is contradictory to the assumption.

Sufficiency proof: Only need to be proved that the mass of any closure is no more than the one of C_s. Any closure C_t can be expressed as $C_t = (C_t \cap C_s) + (C_t \setminus C_s)$. As $(C_t \cap C_s) \subseteq C_s$, then $m(C_t \cap C_s) \leqslant m(C_s)$. From the condition and theorem 2, there does not exist any profitable increment-closure of C_s, then $m(C_t \setminus C_s) = m[(C_t \cup C_s) \setminus C_s] \leqslant 0$. Hence $m(C_t) = m(C_t \cap C_s) + m(C_t \setminus C_s) \leqslant m(C_s)$.

This completes the proof.

4 NUMERICAL METHOD AND GENERAL CRITERION

Upon theorem 3, a basic program of the numerical method for determining the optimum open pit limit can be given as follows.

Step 1:

Let $k = 0$, given the first strong closure $C_k = C_\Phi$.

Step 2:

Let $k = k + 1$.

Step 3:

Search for a strong increment-closure $I_{k,k-1}$ of the current strong closure C_{k-1}. If there is not $I_{k,k-1}$, then go to Step 5. Otherwise go to Step 4.

Step 4:

Let $C_k = C_{k-1} \cup I_{k,k-1}$, go to Step 2.

Step 5:

Terminate. The current strong closure C_{k-1} is a maximum closure.

The numerical method above can be summed up as a general criterion for the optimum design of the open pit limits: searching for a strong increment-closure of a strong closure.

5 CONCLUSION

In principle, the graph theory (Lerchs and Grossman)[3], the network flow (Johnson)[6], the moving cone (Pana)[7] of the computer methods and the pit bottom scheme (Fang Z. and Shi Z.)[8] of the manual methods, determined the open pit limits all upon the general criterion.

The graph theory and the network flow belong to the rigorous methods. It can be proved that the searching for the maximum closure in the graph is equivalent to search for the maximum flow in the network.

The moving cone and the pit bottom scheme belong to the heuristic techniques. The original design criterion of the moving cone is to search for a profitable increment-closure, so the help compensation between the increment-closures will arise, which makes the limit greater than the optimum one. The real trouble is that the moving cone, similar to the pit bottom scheme, simplifies the form of the increment-closures. It is difficult to handle the common compensation between the increment-closures, which makes the limit smaller. So the solutions of the two methods are mostly approximate.

Lemieux's algorithm[9] and Korobov's algorithm[1] are two improved moving cone methods, but in theory and application they can not thoroughly overcome the main technical weaknesses of the moving cone method.

In principle the network flow method and the moving cone method can be traced to the same origin, also in technique they have something in common. A mixed algorithm, with fast calculation and accurate solution, can be obtained by combining the two methods. The improved Korobov's algorithm presented by Dowd and Onur is such an attempt[1].

The dynamic programming method of the computer methods is also a kind of numerical methods[2, 3, 10], but it is different from the methods above in principle. The classical manual method is a mathematical analysis[11, 12].

It is necessary to point out that the numerical methods discussed in this paper have nice operability. Methods of this kind can give not only the final calculating information, but also the stage calculating information in time. Therefore, by making some technical adjustments about the ore body models, these methods can be used to optimize the initial limit, stage limit and production scheduling of the open pit mine.

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