Optimum Design of an Open Pit

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SYNOPSIS

A procedure for designing an optimum pit to yield maximum profit is described. The volume in which a possible pit is considered is divided into discrete blocks, each of which is assigned an economic value equivalent to its worth as a block of mineable material. The profitability of a pit can then be generated by summing the blocks within the pit. The optimizing procedure starts at the surface level and proceeds downwards level by level, to obtain the optimum pit at each level. The method makes use of the fact that an optimum pit at a particular level must be completely contained in any optimum pit at a lower level. Procedures for generating block costs, and pits with various slope angles under the restriction of complete block removal are considered briefly. The main description is of the theory of the method and the computer program based on this. The method is applicable to any type of mineral deposit, the only requirement being that the orebody should be represented accurately by a block model.

INTRODUCTION

Open pit design programs fall mainly into two categories:

(i) *Pit evaluation from a given base.* This type of approach generally facilitates the incorporation of such sophisticated facilities as infinitely variable slope angles so that pits can be constructed very accurately. By using the maximum slope for the pit sides at all times when waste is being mined, the pit profit is kept high, as only the minimum amount of waste will be mined in the design. This method has to be used repeatedly, however, in an attempt to arrive at the optimum. The level, size and horizontal positioning of the base are modified manually. One such method is described by Fairfield, *et al* (1969).

(ii) *An optimum pit design.* This approach which is used to find the optimum pit is used only within a strict set of conditions. (For example, only certain limited pit slopes may be used). Sub-classification of this type of method is given by Johnson, *et al* (1970).

The best method is, of course, a combination of (i) and (ii) above, giving an optimized pit, designed using sophisticated methods. This, however, is not possible at present because of cost and computing considerations.

The method outlined in this paper is of the second type of approach, and was developed as an optimization exercise in three dimensions.

The use of a three-dimensional block model in pit design has been used many times before, Hartman, *et al* (1966), Johnson (1969), Lerchs (1965), Pana, *et al* (1966), etc., and so only a brief mention of it is made in this paper.

It should be noted that no matter how sophisticated a method is used to design a pit, it can never be more accurate than the basic data. The accurate recording and interpretation of assay data are therefore of great importance.

PROFIT MATRIX

The volume concerned is split into small regular blocks. The relative dimensions of the blocks are important as will be seen later, but at this stage a block will be considered as a unit mining block, that is, such a block is of a size that would be treated as either ore or waste, but in either event is considered as an entity which is not divisible.

Associated with each of these blocks the values of the variables that are used to determine profitability must be available. Block profit comes from the evaluation of a function of many variables such as grade of ore, mining costs, transportation costs, price of mineral, etc.[Boyce (1969), Erickson (1968), Sainsbury (1970)].

The three-dimensional grade matrix at Roan Consolidated Mines, Ltd., comes directly from assay calculations conducted during the production of a mineralization inventory for the area. Block maps and contour maps of various types are generated as part of the mineralization inventory and during their compilation into a final report, the required three-dimensional matrix is generated.

Block profit is the actual cost or profit realised by mining or mining and processing a block. Blocks with a positive profit have a final value which covers all costs (mining, production, transport, etc.) whereas negative profit blocks do not.

From the costing equations it is possible to obtain a cut-off grade. Consider a profit function: Profit $= A - B - C$ where A is the revenue from sale of finished metal, B is the production costs, and C is the mining costs.

Clearly A, B and C are all functions and the assumptions have been made that, (i) all variables affecting profit can be considered as part of functions A, B or C, and (ii) blocks of all grades are acceptable for processing. However, low grades may give no finished metal, so $A = 0$. Clearly, if $A < B$ then profit $< -C$. In this case the block would be of very low grade, *regarded as waste* and not processed. This gives $A = B = 0$ and profit $= -C$ (an improvement).

If $A > (B + C)$ then a positive profit is realized from mining and producing. *Regard as ore.*

If $A > B$ and $A < (B + C)$ then by mining and processing the ore a loss is incurred but the loss is less than mining without production. *Regard as ore.*

The cut-off grade is that which produces $A = B$.

By applying the profit function to each block, a block profit matrix is generated. Pit profit is obtained by summing the profit of each block that has to be mined to produce the required pit.

The definition of an optimum pit is taken to be the configuration of blocks (observing the rules of cone generation) whose pit profit is a maximum.

Possibly the easiest way to see this is via the physical analogue described by Lerchs, *et al* (1965) where it is suggested that each block has its calculated profit simulated by a proportional force, positive profit being an upward force, and negative profit being a downward force.

In Fig. 1, the direction of the force is indicated by the arrow and if the system is left to move freely over a short distance,

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some of the blocks will be lifted. As the resultant force through every block (that is, taking into account the effective force from lower blocks on higher ones) in the lifted section must be upward, the removal of any one of these and its supporting blocks must reduce the upward force (and hence the profit) and as the converse is true for the lower section, the separation line must be the optimum pit contour.

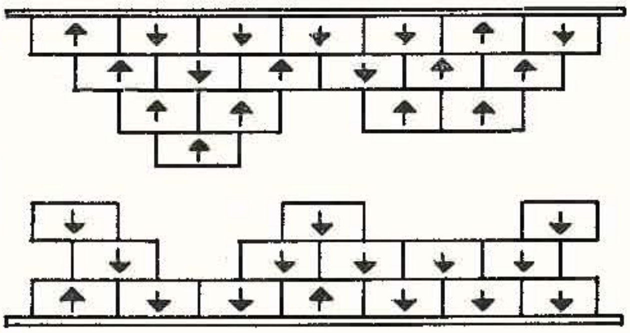

Fig. 1.

CONE GENERATION

A cone (or pit) is generated by the removal of whole blocks from the block matrix. As a pit is to be mined, the slope of the sides must not, of course, exceed the angle of failure and a maximum pit slope must be defined and observed. The pit slope considered here is the average slope generated by a step pattern (as whole blocks are removed). Consequently by considering different step patterns one is regarding various slopes.

Many other authors have considered cone generation, Boyce (1969), Hartman, *et al* (1966), Johnson (1969), Lerchs, *et al* (1965). The method adopted here is that of forming a cone with a single block as base. Two methods are illustrated, using cubic blocks. The next higher level is generated by including the five blocks, in the first method, and the nine blocks, in the second method, immediately above each of the blocks which form the cone so far.

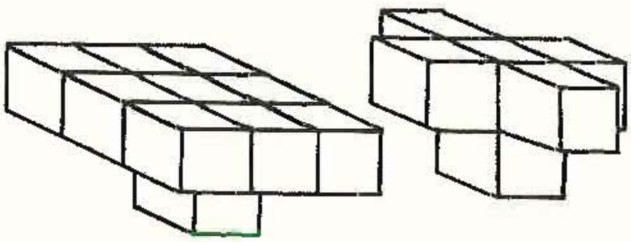

Fig. 2.

The 9:1 method produces a cone with slope ranging from 35° to 45°. The 5:1 method produces a cone with slope ranging from 45° to 55°. By forming levels using the 9:1 and 5:1 methods alternately, an overall 45° slope can be achieved. Gilbert (1966) showed that there are two ways of forming this type of cone and discussed their relative merits.

By changing the dimensions of the block, that is, height to width, the slope produced by the various methods changes and it should be possible in most instances to arrive at block dimensions and a cone generation procedure which will produce a close enough approximation to the required pit slope. Block dimensions must be kept within certain limits. For convenience, the block height is generally the bench depth of the pit but the horizontal dimensions are often completely arbitrary. If the size of the block is too large, however, dilution can occur and the orebody can be completely misrepresented.

In attempts to achieve greater accuracy there is a tendency to reduce the size of the block, but this is often restricted to some extent by drill hole spacing and possibly by the interpolation procedure being used. For a given area, the block size affects the size of the block matrix directly, and hence the size and amount of computing time required by the program, that is, accuracy requires small blocks, and computer economy is achieved with large ones.

It would be possible to optimize using large blocks (possibly built up of smaller blocks in an initial stage. This pit is then taken as a starting point and refinements are made using blocks of smaller size.

Another possibility is to use a large block for evaluation, but bearing in mind that when this block is mined it need not be sent completely for processing or to the waste dump. A more accurate profit for the block would be obtained if part of it were regarded as waste and part as ore, if this in fact were the case. This, of course, complicates the costing function and a dilution factor would have to be considered, but the method could prove useful in saving computer time.

As computer core storage is limited and computing time increased due to the involvement of large arrays, the above ideas may be worth investigating.

THEORY

The theory outlined here is one which continually betters a profitable pit, arriving after a finite number of steps at the optimum.

If one considers the physical analogue of Lerchs, *et al* (1965) with only a fixed number of the upper rows being free to move, then the optimum is achieved for a pit mined to that level. Clearly, the optimum at a particular level must be contained completely in one at a lower level.

The optimum pit is considered to have zero extraction and zero profit until one with a positive profit is found. At each level all blocks with positive profit and every combination of these blocks must be considered as the base of a cone and a financial evaluation made of the cone. Cones are built up from the base (level by level) and if a part cone has negative profit from its base to a certain higher level, then its profit cannot become positive again since all possible cones at higher levels have been investigated and found to produce negative profit; and so its evaluation will cease.

The optimum cone at each level is taken as being mined and is considered to be removed. This means that, in effect, the surface contour of the mineable volume changes constantly and the amount of elements in the block profit matrix with effective values is reduced.

The computation of an optimum pit at each level also has by-product advantages. The method has at any time calculated optimums down to a certain level. The process can therefore be stopped, the initial stages of output used (possibly for short-term planning) and the process re-started from the point at which the latest optimum was generated. The pit could be modified manually before re-starting the computation, or a complete manual pit, at a certain level, can be input.

The fact that only optimum cones are considered on the downward search means that at no stage does a pit contain an area which it is not possible to mine (under the rules of cone structure) and which, by so doing, will increase the profitability. This is always a possibility, however, when a base is specified, as in such a case a certain minimum cone is defined which is included whatever its value may be.

PRACTICAL METHOD

While the theoretical method outlined could be programmed, it is possible to reduce the required calculation drastically while at the same time deviating from the true solution only marginally, if at all.

In the program the costing function which produces the profit matrix is a separate phase. This allows maximum flexibility in calculating block profit. The cone generation procedure is, of course, a more integral part of the program and so the two cannot be separated; however, it is in procedural form so that it can be modified easily. Clearly, having the block profit calculated separately (it is in fact stored on magnetic file) allows the computation to be repeated with different cone generation procedures, but without having to generate the matrix repeatedly.

All matrices required for output can also be held on magnetic storage so that the output reports can be generated by a separate program.

In splitting the program into three steps, each entity has available maximum core utilization and flexibility.

It is thus assumed that a profit matrix has been established and that the required routine for generating a cone with appropriate slopes is available.

During the investigation three cones will be referred to, cone 1, cone 2 and cone 3. Cone 1 is at any time the cone which produces the maximum profit so far.

A search is made on the surface level to see if any profitable blocks (positive block profit) can be found. If they are, they are regarded as being removed and called cone 1.

If the top level is waste, a search is made on the next lower level (and so on down) for a block with positive profit. When a level is found to have at least one block with positive profit then the block with highest profit on that level is noted. This block is taken as the base of a cone. When such a cone is found to have a positive cone profit, then it is taken as cone 1.

Once a cone 1 is obtained, a profitable pit has been found and it is then aimed to better this pit, that is, to find a new pit with greater profit.

Given a cone 1 with one block as its base, surrounding block tests are made. Initially, the surrounding block test takes the eight blocks horizontally surrounding the base block in turn and forms a cone with the block as base (cone 2). Cone 3 is determined to be the union of cones 1 and 2. The best cone of these three is now taken as cone 1 and the search continued. Once the eight blocks have been considered, if the original (one-block base) cone 1 is improved, a search is conducted on the surrounding base blocks of the new cone 1, etc. When the surrounding block search gives no improvement the search moves to the next lower level.

At each new level consideration is given to whether improvement can be achieved by removing blocks directly below the pit base. If so, they are removed and the same test applied to the next lower level.

Once this form of improvement cannot be achieved at a particular level, the most profitable block is found at this depth and a cone 2 formed; cone 1 is already present and the union gives cone 3. If subsequent testing gives a new cone 1 at the lower level, that is, one-block base, then the process continues from the point of testing surrounding blocks. If not, a best-block search is made at consecutive lower levels until an improved (new) cone 1 is found or until the pit base level limit is achieved.

Once the pit has been evaluated in this way down to the base level, the cone 1 is then regarded as being mined. The process is repeated, with the previous cone 1 stored and its boundary becoming the new surface, to pick up extensions or new pits. The iteration continues until a full search gives no improvement. The pit design is then complete.

Variations on the method outlined have been considered. Modifications such as limiting the number of surrounding block searches on each level, inputting a starting level for the search (useful when the top levels are known to be waste) and doing a best-block and surrounding block search on a level that has been expanded to by accepting exposed economical blocks as an initial pit extension to the level, were found to affect efficiency and computing speed with very little change in the final design.

The program was written in PL1 and run on an IBM 360 model 40. A block matrix containing over 13 000 elements can be accommodated in 120K bytes of memory. The only comparative figures available at the present time are for a complete run (block profit generation, optimization and output) which took three hours, using full matrix capacity and produced an improvement of three per cent over the manual design.

It was stated initially that a method for optimizing open pit design but using sophisticated techniques was the answer to choosing between one or the other. It is suggested that having an idea of the optimum pit positioning as generated by the type of method outlined here and then using a more sophisticated approach such as described by Fairfield, *et al* (1969) would be the means at present for getting as close as is possible to the best solution.

ACKNOWLEDGEMENTS

The author wishes to thank the management of Roan Consolidated Mines Ltd., Zambia, for permission to publish this work and Messrs. M. Hancock and J. Perry for their comments and queries which proved invaluable.

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