An approach towards ascertaining open-pit to underground transition depth

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Abstract
In this study, in order to determine OP to Ug mining TD of tabulate deposits, through various states some formulas were concluded. These formulas resulted based on the allowable and overall stripping ratios. For this objective, an analytical procedure was served. The contemplated states are variously combined from the deposits with outcrops or overburden and including maximum or minimum possible pit floor width.
Keywords: Transition depth, tabulate deposit, stripping ratio, allowable, overall, analytical procedure.

1-Introduction

As a rule, Open-Pit (OP) method is considered to be more approvable and dominant than Underground (Ug), especially in recovery, production capacity and mechanization, grade control and cut off grade, ore lose and dilution, flexibility, safety, and so on (Bakhtavar & Shahriar, 2007). Even though, Ug mining is more acceptable from environmental (for instance, Ug will often have a smaller footprint than an OP of comparable capacity) and social considerations (Chadwick, 2008). As well as, in especial condition due to ore deposit geometry and increasing of deposit depth, Ug methods must be employed.

Many deposits can be mined entirely with OP method; others must be worked Ug from the very beginning. Still other deposits are the near surface deposits and have considerable vertical extent (Bakhtavar et al., 2008). Although they are initially exploited by OP mining, there is often a point where decisions have to be made to either continue deepening the pit or mining the same deposits by Ug methods (Flores, 2004).

Up to now, the studies connecting to determine TD from OP to Ug mining have been done just in recent decade and in order to solve the transition problem of a number of mines with combinational potential. Finally, a few numbers of them led to an optimal basic method.

The first method for the aim named Allowable Stripping Ratio (ASR) which was expressed by a relation with emphasis on exploitation cost of 1 ton ore in Ug and in OP, as well as, removal cost of waste in relation to 1 ton of ore extracting using OP (Soderberg & Rausch, 1968).

In 1982, an algorithm by Nilsson based upon cash flow and Net Present Value (NPV) was presented (Nilsson, 1982). Then, in 1992 for highlighting the TD as an important issue connecting to deposits with combinational extraction, the previous algorithm (in 1982) was again represented and reviewed (Nilsson, 1992). As well as, in 1997, in addition to state the TD topic he underlined discount rate as a most serious parameter in the process (Nilsson, 1997).

In 1992, other algorithm for this target was introduced by Camus. This algorithm was based on block models and considering net economic values of blocks relating to OP and Ug exploitation. The approach consists basically in running the OP algorithm taking into account an alternative cost due to the underground exploitation (Camus, 1992).

Whittle programming (4-x) which has been developed to assist in the interfacing of OP and Ug mining methods was argued and studied in 1998. Due to the applied method in

the programming, management can make decision based on quantified operational scenarios considering to the OP to Ug transition (Tulp, 1998).
In 2001 and 2003, an approach with “Allowable Stripping Ratio” method based on and in mathematical form for the objective was introduced. Volume of ore and waste within the pit limit were assumed as a function of constant (ultimate pit) depth (Chen et al., 2001 & 2003).
A heuristic algorithm in 2007 during designing software for determining optimal TD from OP to Ug, was displayed (Visser & Ding, 2007).
In this year (2007), a heuristic algorithm on the basis of Economic Block Model (EBM)s with OP and Ug block values was also introduced. The main process in the algorithm is comparison between total values of OP and Ug in each level (Bakhtavar & Shahriar, 2007).
Majority of the presented methods have a heuristic base. So to get valid results, it is essential to establish a fundamental and reliable method as an effective solver tools. For this reason, the main target of this paper is introducing a fundamental and reliable method based on an analytical procedure and by employing ASR to find out TD from OP to Ug mining.
In this way and in choice between OP and Ug mining methods, it is necessary to compare their operation economic efficiencies, with the exception of when the advantages of one of them are entirely obvious. The main characteristic employed in economic evaluation of OP mining is the Stripping Ratio (SR), by which is on the whole meant the volume of removed waste per unit of mineral (m3 per m3, or m3 per ton).
The parameter known as the SR is almost universally used and represents the amount of uneconomic material that must be removed to uncover one unit of ore (Hartman, 1992).
If a deposit changes abundant in geometry along the dip, above all if the change occurs at the end of the deposit, the SR will be too large when the whole deposit is mined via OP mining (Bakhtavar & Shahriar, 2007).
In relation to the practice of surface mining of coal deposits, it is common to describe the SR in terms of m3 of waste per ton of the mineral, but in operating ore deposits the mentioned ratio is ordinarily given in terms of m3 of waste per m3 of the related mineral.
There are various kinds of SR classified as overall, instantaneous (operating), break-even, and allowable.
Overall Stripping Ratio (OSR) is the proportion of the whole volume of overburden in the OP to the total reserves of the mineral. In other words, according to relation 1, the ratio of the total volume of waste to the ore volume is defined as OSR (Hartman, 1992).

$$OSR = \frac{volume\ of\ \ waste\ removed\ to\ a\ certain\ depth}{volume\ of\ \ ore\ removed\ to\ a\ certain\ depth} \qquad (1)$$

To determine maximum depth based on the profitability of the operation, it is essential to know about the overall costs and revenues that will be received by selling the ore and its bye-products, if any (Tatiya, 2005).
To develop a pit design requires the establishment of the Break Even Stripping Ratio (BESR). This ratio refers only to the last increment mined along the pit wall. In other words, BESR is applied only at the surface of the final pit and must not be confused with the OSR, which is always less; otherwise there would be no profit to the operation (Soderberg & Rausch, 1968).

The BESR is calculated for the point at which break-even occurs and the necessary stripping is paid for by the net value of the ore removed. Generally, the BESR can be determined due to relation 2 (Taylor, 1972):

$$BESR = \frac{I - C_t}{C_{sw}} \quad (2)$$

Where;
I: revenue per tonne of ore
Ct: production cost per tonne of ore (including all costs to the point of sale, excluding stripping)
Csw: stripping cost per tonne of waste
The Allowable Stripping Ratio (ASR) characterizes the maximum scope of stripping which is practicable in OP operation. The ratio stated in terms of m3 of waste per ton of the mineral can be determined in accordance with the relation 3.

$$ASR = \frac{C_{ug} - C_{op}}{C_w} \quad (3)$$

Where,
Cug: full prime cost of 1 ton of the mined mineral via underground (Dollars);
Cop: prime cost of 1 ton of the mined mineral via OP (minus expenses of waste removal), in Dollars;
Cw: total costs of 1 m3 of ground removal via OP mining (Dollars)
The ASR can be engaged during economic evaluation process of OP operation and finding out Transition Depth (TD).
It should be also considered that the ASR mainly depends on the nature and extent of mechanization of OP mining.
In most pit designs, the OSR is much lower than the allowable maximum limiting ratio (meaning ASR). Accordingly, the limiting ratio is never apparent in the year to year operating (instantaneous) stripping ratios.
Instantaneous Stripping Ratio (ISR) is the real relation of the removed waste volumes and the mineral exploited in the pit during a certain and definite period of time.
The authors seek to inference some relations based on the initial relation (3) helping to determine TD from OP to Ug. For this target, an analytical procedure was employed, which is unacceptable with extremely intricate-shape deposits; therefore, in the study tabulate-shape deposits were served.
2- 2D analytical model for determining TD
In the study, based upon 2-D analytical method and due to the four following states, various formulas to ascertain TD over from OP to Ug for the uniform and tabulate ore deposits were proved.
State 1- If deposit includes outcrops and maximum width of pit floor;
State 2- If deposit includes outcrops and minimum possible width of pit floor;
State 3- When deposit includes overburden and maximum width of pit floor;
State 4- When deposit includes overburden and minimum possible width of pit floor
In addition, in order to increase the accuracy of the all formulas the authors considered both ore recoveries acquired through OP and Ug mining methods.

For the target, all mentioned states are analyzed in detail due to four separate sections as following:

2-1- Deposit with outcrops and maximum width of pit floor

In first state it is assumed a tabulate ore deposit includes outcrop and width of the deposit and pit floor are equal, in other hand, it signifies entire width of the ore deposit located in pit floor is planned to mine through OP method (Fig 1). At the final pit depth, the OSR becomes equal to the ASR. Thus, for the target of this study, it is necessary to equate the OSR and ASR (relation 4).

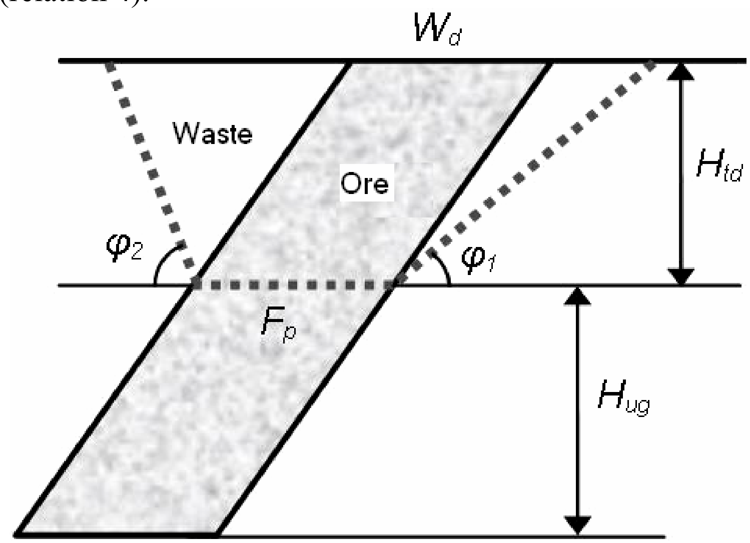

Figure 1: TD of tabulate deposit with outcrops and including maximum width of pit floor

$$OSR = ASR \Rightarrow \left[\frac{W}{O}\right] = \left[\frac{C_{ug} - C_{op}}{C_w}\right] \quad (4)$$

Where,

OSR: overall stripping ratio

In this case, initially it is necessary to measure covered waste rocks and the related ore within the pit limits area. Then, utilizing a geometric analytical procedure and the mentioned equivalent, relation (formula) 5 is proved and deduced.

$$H_{td} = \frac{W_d \cdot \left(R_{ug} \cdot C_{ug} - R_{op} \cdot C_{op}\right)}{C_w \cdot A} \quad (5)$$

Where,

Htd: transition depth (m)

Wd: horizontal thickness of the ore body (m)

Rug: ore recovery coefficient via Ug method

Rop: ore recovery coefficient via OP method

φ1: pit side slope angle along foot-wall (deg)

φ2: pit side slope angle along hanging-wall (deg)

A= cot φ1+ cot φ2

It is notable that in the formula 5 and in all next formulas, different coefficients of ore recovery for OP and Ug were taken into account.

2-2- Deposit with outcrops and minimum possible width of pit floor

Second state is as the same as the first (previous) state, with the exception of this case just minimum possible width of pit floor may be mineable (figure 2). It taking into considers the eventual deepening of the OP without extending it sidewalls. Due to the difference, and basis of equivalent of OSR and ASR (relation 4), to determine TD from OP to Ug, relation 6 is concluded. In the deduced formula (6), in addition to the waste rock and ore areas regarded in first state, there is a trapezium area of ore with height of H2 must be added.

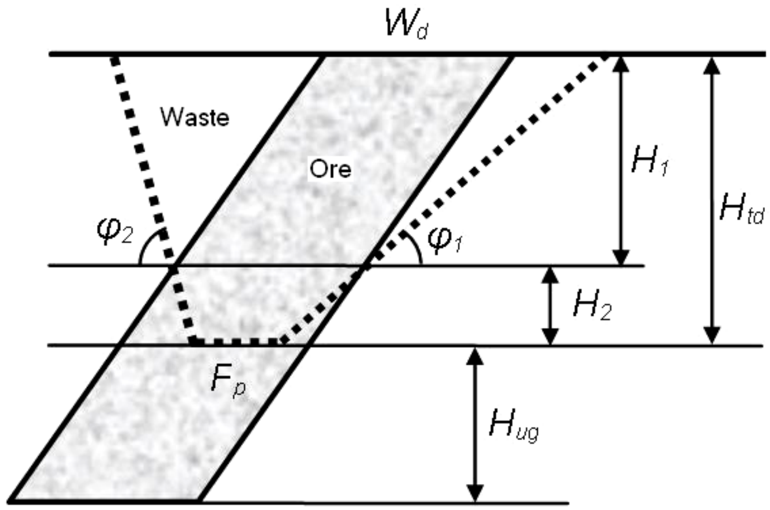

Figure 2: TD of tabulate deposit with outcrops and including minimum possible width of pit floor

$$H_{td} = H_1 + H_2 \Rightarrow$$
$$H_{td} = \frac{W_d \cdot \left(R_{ug} \cdot C_{ug} - R_{op} \cdot C_{op}\right) + (W_d - F_p) \cdot C_w}{C_w \cdot A} \qquad (6)$$

Where,
H1: pit depth in ore with extension sideways (m)
H2: deepening of pit depth without extension sidewalls (m)
Fp: minimum possible width of the pit floor (m)
All the other variables are defined in the previous sections.

2-3- Deposit with overburden and maximum width of pit floor

In third state, as demonstrating in figure 3, is as the same of first state conditions but in stead of outcrops there is an overburden with a constant thickness over the ore deposit. It means that in some cases, maybe ore deposits don’t include any outcrops (figure 3). For this matter, relation 7 is deduced. In the formula, besides the waste rock and ore areas included in first state, a trapezium area of overburden with height of Hov must be added.

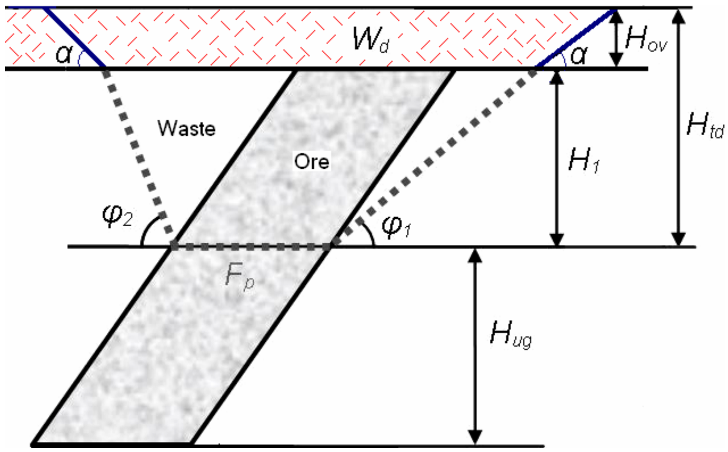

Figure 3: TD of tabulate deposit including overburden and maximum width of pit floor

$$H_{td} = H_1 + H_{ov} \Rightarrow$$
$$H_{td} = \frac{\{W_d \cdot (R_{ug} \cdot C_{ug} - R_{op} \cdot C_{op}) \cdot [2B + A]\} + [C_w \cdot (W_d - F_p) \cdot A]}{2C_w \cdot B \cdot A} \qquad (7)$$

Where,
Hov: overburden thickness (m)
α: pit side slope angle within overburden (deg)
B= cot α
The other variables are defined in the previous relations.
2-4- Deposit with overburden and minimum possible width of pit floor
Finally, the forth state (figure 4) is represented if there is overburden with a constant thickness over an ore deposit, namely it assuredly doesn't include any outcrops; on the contrary beginning of the deposit is from a clear depth (Hov). This state is a combination of the second-third states. In this case, according to the relation 4 and alike the prior procedures, to calculate TD relation 8 can be worked. In this formula, besides the overburden, waste rock and ore areas considered in third state, a trapezium area of ore with height of H2 must be added.

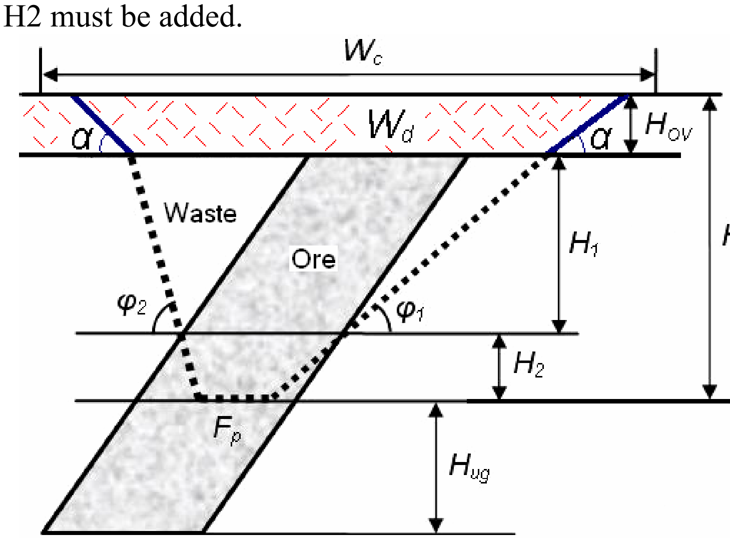

Figure 4: TD of tabulate deposit including overburden and minimum possible width of pit floor

The lengthy base of overburden trapezium (Wc) which must be placed within the formula 8, can be calculated as below relation.

$$H_{td} = H_1 + H_2 + H_{ov} \Rightarrow$$
$$H_{td} = \frac{\{W_d \cdot (R_{ug} \cdot C_{ug} - R_{op} \cdot C_{op}) \cdot [2B + A]\} + [C_w \cdot (W_c - W_d) \cdot A]}{2C_w \cdot B \cdot A} \qquad (8)$$

$$W_c = 2H_{ov} \cdot B + \frac{W_d \cdot (R_{ug} \cdot C_{ug} - R_{op}.C_{op})}{C_w} \cdot W_d$$

All variables are defined in the previous relations.
It is evident that between the previous presented states, the last one is more common and complex.

3- Conclusion

Selection of mining method is one of the most important decisions in the design stage of mine and before development.

In relation to the deposits which have potential of using the combined mining of OP and Ug in vertical direction, the most significant problem is the TD determination over from OP to Ug mining. For this target, in the study, serving the analytical method for the uniform and tabulate ore deposits and due to the four states, some formulas were deduced (in this way, the OSR and ASR made basically equate).

First, in regard to the tabulate deposits including outcrops and considering the maximum width of pit floor for exploitation, a simple effectual formulate was proved. In the second case, to get to take into account the eventual deepening of the OP without extending it sideways, in stead of maximum width, minimum possible width of pit floor was contemplated. In this way, the inferred formulate in respect to the initial case are more complex. Through the both remained states, two other formulates based on the ore deposit taken place below a certain thickness of overburden, and related to the maximum and minimum possible width of pit floor, were derived.

The significance and usability of the presented formulas will be achieved due to utilizing them for ascertaining TD of some various practical cases. In this way, modification and improvement of the formulas will be possible.

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