Justification criteria for open pit mine depth and mining/haulage machinery parameters

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Abstract. The paper presents results of studies into criteria for joint justification of open pit mine depth and mining/haulage equipment parameters. New indexes of mineral reserves appraisal are obtained, and a classification of mineral reserves by value is proposed. In terms of a specific deposit, the relations are given for prompt determination of shovel bucket and dump truck capacities, and for justification of rational pit depth under conditions of unstable market of mineral reserves.

1. Introduction

Justification of ultimate pit depth limit is of special concern in ore mining. It defines basics of open pit mining and its key technical and economic indicators. At the same time, solution of this problem depends on many factors and requires complete and precise calculations with many complex questions explained. Under worsening natural and engineering conditions of mining, or in economic instability, it is necessary to estimate open pit mine dynamic, characteristics of modern mining and haulage machinery and to predict possible risk and new capabilities.

In Russia, the ultimate pit depth limit is conventionally set based on open pit mining without loss. The limit and boundary stripping ratios are determined and they should obey the condition that:

\[ H \in K_b \leq K_{lim}, \]

where \( H \) is the pit depth, m; \( K_b \) is the perimeter stripping ratio, m\(^3\)/t (t/t); \( K_{lim} \) is the limit stripping ratio, m\(^3\)/t (t/t).

The boundary stripping ratio is found as the ratio of rock volume increment to ore volume increment with increase in the ultimate pit depth limit by one bench, and the limit stripping ratio is calculated based on unit production cost of mineral:

\[ K_{lim} = \frac{C_{al} - C_{mp}}{C_{st}}, \text{ m}^3/\text{t}, \]

where \( C_{al} \) is the allowable cost per 1 t ore, Rub/t; \( C_{mp} \) is the cost of mining, concentration and metallurgical processing of 1 t ore and other costs, excluding stripping, Rub/t; \( C_{st} \) is the cost of stripping, Rub/m\(^3\).

The allowable cost per 1 t ore is found from the formula:

\[ C_{al} = \frac{PC(1-d)R}{1+E_n}, \text{ Rub/t}, \]
where $P$ is the market price of the mineral, Rub/t; $C$ is the useful component content of ore, g/t; $d$ is the ore dilution coefficient, unit fractions; $R$ is the useful component recovery in processing, unit fractions; $E_{pp}$ is the profit rate, unit fractions.

The economic criterion of profit in open pit mining can be given by:

$$E_{Pr} = P \cdot C \cdot R (1 - n) - (C_{opm} + C_{st} \cdot K_s + C_{proc} + C_{exp}) \left(1 - \frac{n}{1 - d}\right), \text{ Rub/t},$$

(4)

where $n$ is the ore loss coefficient, unit fractions; $C_{opm}$ is the cost of open pit mining, Rub/t; $C_{st}$ is the cost of stripping, Rub/m$^3$; $C_{proc}$ is the cost of processing of 1 t ore, Rub/t; $C_{exp}$ is the general and other expenses, Rub/t.

In case the profit calculated from (4) is higher or equal to zero, the ore reserves within the open pit mine limits are assumed as economic reserves minable and processable with the available advanced technologies and equipment. When the profit value is under zero, the ore reserves are assumed as uneconomic reserves as their mining is economically inexpedient or technically and technologically impossible although they can be assumed economic reserves in the future [1]. Justification of economic reserves in accord with the effective classification [2] takes into account categorization of ore reserves in terms of the extent of their exploration: categories A, B, C1 and C2.

At the further stages of mine planning, design and operation, neither volume not quality estimates are changed. During mining of a deposit, some portion of total reserves, depending on the degree of there preparation for mining, is grouped into prepared, accessed and ready for mining reserves.

The prepared reserves are the reserves that can be involved in primary process flow charts before extraction-and-loading; accessed reserves are the reserves with transport access required for extraction and haulage; ready for mining are the accessed reserves ready for extraction, loading and haulage directly from rock mass, or after pre-treatment by ripping or blasting [3].

The present paper authors think that this approach needs system amendments. This is mostly connected with the justification of the threshold limit of economic efficiency of reserves, with regard to the cost behavior as open pit mine depth is increased, inflation and possible price variation, including the given mineral price.

2. Justification criteria for open pit mine parameters

The review of open pit mining and mineral markets shows that for the latest 15–20 years, some open pits have reached the depth more than 500 m while their annual rock mass output has more than doubled in the conditions of time-varying demand for minerals and price level [4]. Moreover, geographically, open pit mining drifts to the regions with severe climate, which complicates mining technologies. Open pit mines are limited in terms of size as their depth is increased, which results in nonuniform development of the open pit mine area [5]. One the other hand, progression of mining and haulage machine engineering with increased capacity more than 1.5 times offers some technological advantages [6, 7].

The increase in capacity of open pit mining machines was gradual and conditioned mainly by reequipment of open pit mines, while the prices set by the machine manufacturer as well as market prices of of minerals jumped depending on currency rates. For example, gold price as per data of the Central Bank of Russia was 689 Rub/g (859 $/oz), in 2008, 1201 Rub/g (1230 $/oz) in 2010, 1436 Rub/g (1396 $/oz) in 2013 and 2362 Rub/g (1260 $/oz) in 2018. The average purchase coat of import equipment, e.g. manufactured by Caterpillar or Komatsu, at the elevation of dollar rate relative to rubble in 2014–2015 from 33 to 73 Rub in Russia, jumped by 1.8–2 times.

All these changes required multiple refreshed justifications of depth and other related parameters of open pit mines at different stages of planning and design, and governed high significance of assessment of technological advance rate in mineral mining relative to the rate of deletion of mineral reserves.

In this regard, the present paper authors have attempted to propose new justification criteria which are believed to be capable to enhance reliability and promptness of decision-making after being adapted to the specific deposit conditions. The background of the approach is feasibility of rating of
any mineral reserves by value based on preset classification and possibility of finding ration open pit mine depth based on parameters of employed mining and haulage equipment, as well as its purchase and operation cost dynamics.

The proposed expression for the mineral value \( V \) is:

\[
V = \frac{P \cdot C \cdot R \cdot (1 - n)}{(C_{\text{opm}} + C_{\text{st}} K_h + C_{\text{proc}} + C_{\text{exp}}) \frac{1-n}{1-d}}.
\]  

(5)

The joint analysis of the formulas (4) and (5) shows that: when \( EPr \geq 0, \ V \geq 1 \) and when \( EPr < 0, \ V < 1 \). On this basis, the value rating of mineral reserves is proposed: \( V < 1 \)—no value (uneconomic); \( 1 < V < 1.25 \)—low-value (poor); \( 1.25 < V < 1.5 \)—medium value (low-grade); \( 1.5 < V < 1.75 \)—of value (ordinary); \( V > 1.75 \)—high-value (high grade, rich).

In view that the common criteria of absolute and relative efficiency of investment projects are currently net present value \( NPV \) and internal rate of return \( IRR \), they are correlated with the above characteristics as follows:

\[
NPV = f(EPr), \quad IRR = f(V).
\]

Calculation of these relations in optimization of open pit mine limits will offer more exact dynamics of open pit mining, allow planning of extraction volumes and improve ability of a company to respond to different unstable situations on the mineral market.

The values of \( NPV \) were calculated from the known formula:

\[
NPV = \sum_{t=1}^{T} \frac{R_t - E_x_t}{(1 + E_{\text{co}})^t},
\]

where \( T \) is the estimation period, years; \( R_t \) is the income at a \( t \)-th calculation step, Rub; \( E_x_t \) is the expenses at this step, Rub; \( E_{\text{co}} \) is the industry-average rate of discount, %.

The values of \( IRR \) were set as the positive rate \( E_{\text{av}} \) such that \( NPV \) is zero. Assuming that the pit depth \( H \) would satisfy that condition under most unfavorable conditions, the optimal value domains of the studied parameters were predicted.

The expenses \( E_{x_t} \) in (6), embracing both operating costs and investments, for the main variants of mining and haulage machines available on the market in Russia were calculated directly. The correct evaluation of these expenses is one of the critical and labor-consuming stages in justification of economic efficiency of open pit mining. The calculations need much information which is always available. The expenses should be forecast for the long term comparable with operation life of equipment.

**Figure 1.** Effect of open pit depth \( H \) on average bucket capacity \( E_{\text{buc}} \) of electric shovels manufactured by IZ-KARTEKS, UZTM, and on capacity \( q \) of dump trucks manufactured by Caterpillar, Komatsu, Terex, Hitachi, Liebherr in mining of ore reserves of different value \( V \): (a) 1; (b) 1.25; (c) 1.5; (d) 1.75.
The calculations were performed for open pit mines operating in rock mass with different physical and mechanical properties and in different climatic conditions. The rate of discount $E_{av}$, reflective of the inflation level, was assumed in the range from 10 to 20%. The values of the other indexes in (4)–(6) and their possible combinations were set such that to ensure the mineral value $V$ in the range from 1 to 1.75. Some results are depicted in the Figure 1.

The presented relations are valid for a round open pit mine, column-like ore body and rock mass having ultimate compression strength to 120 MPa, density of 2.85 t/m³, average structural block size of 1 m, and agree with the research findings in [8, 9]. Alongside shovels and dump trucks, the basic equipment package includes drill rigs and dozers. The number of buckets unloaded to a truck body is from 3 to 7.

3. Conclusions
It follows from the analysis of the obtained results, that the open pit mine depth is tightly connected with both value of ore and parameters of mining and haulage machines. Technical excellence of modern mining machines and their elevated capacity makes it possible to reach high productivity and expand open pit mine limits at higher economic efficiency.

The propose criteria enable justification of mining technology and equipment at the extended classification of mineral reserves.

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