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Economic and technological aspects of interrelation between open pit mine depth and mining transport parameters

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Abstract

Introduction. *This paper presents the results of research on ore pit depth justification in relation to mining transport parameters.*

Research theory. *Features of the current state and further development of deep pits are considered. There is also the classification of fields by relative excavation difficulty depending on physico-technical features of rock, conditions of their occurrence and climate severity. Besides, extractable ore reserves are classified depending on its value. The indicators for joint justification of excavation difficulty, ore pit depth, mining transport complexes parameters have been offered as well as their established optimal regions.*

Results and conclusions. *The dependences have been obtained allowing to efficiently determine excavator bucket capacity and dumptruck load-lifting capacity and validate pit depth taking into account ore value. It has been determined that when mining a deposit of corresponding excavation difficulty with an opencast method, cost behavior changes with depth due to the increase in power, productivity, and power-weight ratio of drilling rigs, excavators, dump trucks, and bulldozers; cost behavior is of an increasing nonlinear character. Rational uses of mining transport complexes based on electric and hydraulic excavators have been singled out. The reasons of their probable change have been estimated. Research results have been approved when planning the largest gold ore pit in Russia, Vostochny pit of Olimpiadinsky gold ore field.*

Key words: *open pit mine depth; excavator bucket capacity; dump truck loading capacity; profit; net present value; internal rate of return; ore value.*

Introduction. At the present time effective operation of mining enterprises largely depends on the type of location, properties of mined rock, condition of their occurrence, applied mining transport, operation scale and world market requirements. Further development of ore fields opencasting at such enterprises, as a rule, is conditioned on the growth of pit depth and rock transportation distance; it is also connected with the alternation of physical and mechanical characteristics of rock, content of commercial elements in ore, and production cost behavior.

In fact, national and foreign experience together with the forecast from Grand View Research (http://www.grandviewresearch.com), BMI Research (http://bmiresearch.com), Parker Bay (http://parkerbaymining.com) etc. show that in the nearest future opencasting will be the most economical and effective mining method. By means of developing new equipment and technology, reducing extraction and overburden removal costs [1, 2].

However, at the present time the depth of a range of ore pits throughout the world has already exceeded 700 m, and rational equipment selection for these conditions speciifed a lot of problems for mining theory and practice [3, 4].

In Russia the solution to this problem is greatly complicated by the fact that mining activity is carried out in the regions with severe climate characterized by low air temperatures with large temperature change over a 24-hour period and in the course of a season, heavy precipitation and other adverse factors. For instance, in Yakutia and in the north of the Krasnoyarsk region diamond and gold pits depth has already reached 500–600 m.

Pits are developed in hard rock using the technology which is based on excavating and automobile complexes; development is carried out step-by-step with temporary preservation of slopes and working benches. For the last 15–20 years the applied schemes of mechanization, stripping and planning have ensured annual rock capacity growth more than twofold under machine capacity growth by 1.5–2 times.

Table 1. Fields classification by relative excavation difficulty
Таблица 1. Классификация месторождений по относительной трудности разработки

Field class according to excavation difficulty	Category	Field parameters					
		σ_{compr}, MPa	γ, t/m^3	l_m, m	H_p, m	L_{tr}, km	S, mark
1. Easy	1, 2, 3, 4, 5	≤ 40	≤ 1.8	≤ 0.4	≤ 200	≤ 3.0	≤ 50
2. Intermediate	6, 7, 8, 9, 10	> 40 ≤ 80	> 1.8 ≤ 2.4	> 0.4 ≤ 0.6	>200 ≤ 320	> 3.0 ≤ 4.5	> 50 ≤ 65
3. Difficult	11, 12, 13, 14, 15	> 80 ≤ 120	> 2.4 ≤ 2.9	> 0.6 ≤ 1.0	>320 ≤ 500	> 4.5 ≤ 7.0	> 65 ≤ 80
4. Very difficult	16, 17, 18, 19, 20	> 120 ≤ 160	> 2.9 ≤ 3.3	> 1.0 ≤ 1.8	> 500 ≤ 700	> 7.0 ≤ 10.0	> 95 ≤ 110
5. Extremely difficult	21, 22, 23, 24, 25	> 160	> 3.3	> 1.8	>700	>10.0	> 110

Step by step pit development has made it possible to defer significant part of stripping activity to later periods and recover with newer and more advanced equipment, but it's also limited working zone and reduced working areas for the equipment.

All the indicated circumstances together have defined that it is necessary to expand some important scientific and practical solutions to justify the boundaries of ore fields opencast mining and to rationally distribute equipment complexes over the depth of pits; first, it should be done in relation to physical and technical characteristics of the mined rock and their occurrence conditions, second, to the types and parameters of the required equipment and workflows technology and organization [5, 6], and third, to price volatility and inflation in the world market [7].

In this regard, the research has been carried out, the results of which have been generalized and expanded in this article.

Research methodology. Labor intensity and technical and economic efficiency of opencast mining is predetermined by a lot of factors and parameters. Rock strength, planform depth and dimensions, ore and overburden transportation distance, and natural and climatic characteristics are the most significant factors.

These factors influence can be traced according to figures provided in table 1, which is the classification of fields obtained from the results of the research [8, 9]. In table 1 σ_{compr} is the compressive strength, MPa; γ – rock density, t/m^3; l_m – mean size of a block, m; H_p – pit depth, m; L_{tr} – transportation distance, km; S – climate severity according to P. I. Kokh.

Therefore, the depth is a key parameter of a pit and in order to determine its rational value it is principally required to establish the cost behavior of mining performance by this or that combination of mining transport under a particular technology and rock characteristic.

It is known that according to the practice of Russian design, ore pit depth is traditionally established according to the break-even field development of this or that structural complex mechanization.

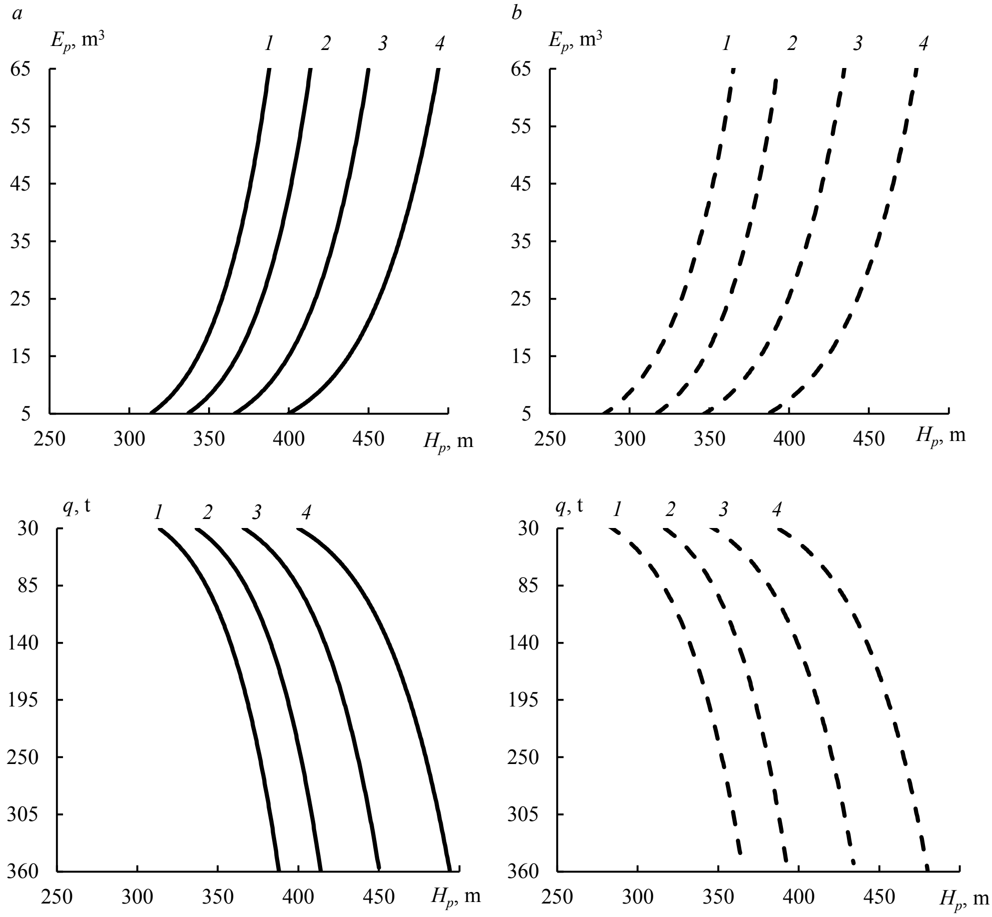

Fig. 1. Influence of an ore pit depth on the average electric excavators bucket capacity and dump trucks loading capacity while mining the III class of difficulty with the relation $L_k/B_k = 1$ and distinction of indicators:
a – E_{co} = 10%; *b* – E_{co} = 15%; 1 – B = 1; 2 – B = 1.25; 3 – B = 1.5; 4 – B = 1.75

Рис. 1. Влияние глубины рудного карьера на среднюю вместимость ковша электрических экскаваторов и грузоподъемность автосамосвалов при разработке месторождения III класса трудности с отношением $L_к/B_к = 1$ и различии показателей:
а – E_{co} = 10 %; *b* – E_{co} = 15 %; 1 – B = 1; 2 – B = 1,25; 3 – B = 1,5; 4 – B = 1,75

For this purpose, economic and incremental stripping ratios are determined, and the following condition is checked:

$$H_p \in K_i \in K_e.$$

Incremental stripping ratio K_i is found as a ratio between rock volume increment to rock volume increment under pit total depth rise by one bench, and economic stripping ratio K_e, m^3/t, is calculated from the production cost of a unit of mineral:

$$K_e = \frac{C_a - C_p}{C_{str}},$$

where C_a – allowable cost-per-ton, ₽/t; C_p – cost of production, processing and metallurgical extraction of 1 ton of ore and other costs without stripping, ₽/t; C_{str} – cost of stripping, ₽/m^3.

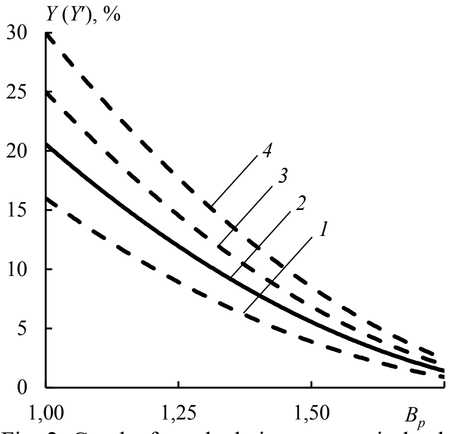

Fig. 2. Graphs for calculation an ore pit depth according to the ore value and discount rate:
1 – E_{co} = 5 %; *2* – E_{co} = 10 %; *3* – E_{co} = 15 %; *4* – E_{co} = 20 %

Рис. 2. Графики для расчета глубины рудного карьера при различии ценности руды и нормы дисконта:
1 – E_{co} = 5 %; *2* – E_{co} = 10 %; *3* – E_{co} = 15 %; *4* – E_{co} = 20 %

As a rule, profit P is used as a basic economic criterion when setting ore reserves limited by an open pit. If the estimated value of profit is greater than or equal to zero, than ore is ascribed to commercial ore, i.e. reserves the use of which is economically sound under available or utilized engineering and technology of production and processing. If the estimated value of profit is less than zero, than ore is ascribed to unpayable ore, i.e. reserves the use of which in the present time is economically inadvisable or technically or technologically impossible, but which can be further transformed into commercial [9, 10].

As soon as in the conditions of any field it is possible to divide the reserves according to their value based on the given classification, an expression has been proposed to calculate the appraisal indicator of ore value:

$$B = \frac{\mathrm{PCR}(1-n)}{(\mathrm{C}_p + \mathrm{C}_{str}K_i + \mathrm{C}_{proc} + \mathrm{C}_{other})(1-n)/(1-p)},$$

where P is the price of a mineral in the market, ₽/g; C – grade of ore, g/t; R – processing recovery of a mineral, unit fraction; C_p – cost of ore opencast production, ₽/t; C_{proc} – cost of 1 ton of ore processing, ₽/t; C_{other} – general business and other expenses, ₽/t; n – the ratio of ore production loss, unit fraction; p – ore dilution factor, unit fraction.

So, the following has become obvious: if P ≥ 0, then $B \geq 1$; if P < 0, then $B < 1$.

With this consideration in mind, it is proposed to divide the reserves according to value as follows [11]:

$B < 1$ – ore which does not possess any value (unpayable ore);

$1 < B < 1.25$ – ore of little value (low-grade ore);

$1.25 < B < 1.5$ – ore of medium value (base ore);

$1.5 < B < 1.75$ – valuable ore (run-of-mine ore);

$B > 1.75$ – ore of high value (high grade ore).

As soon as net present value *NPV* and internal rate of return *IRR* are currently generally accepted criteria of investment projects absolute and relative effectiveness correspondingly, the dependences between them and the previously considered criteria have been established:

$$NPV = f(\Pi);\ IRR = f(B).$$

The values of *NPV* and *IRR* have been calculated with the account of net present value dynamics and annual expenditures. *IRR* has been determined as a positive norm of discount E_{co}, with which *NPV* would be equal to zero.

Table 2. Rational uses of the equipment complexes with electric excavators
Таблица 2. Области рационального применения комплексов оборудования с электрическими экскаваторами

Excavator bucket capacity E_b, m^3	Ore pit depth H'_p, m, depending on the parameters							
	L_p/B_b = 1–2				L_p/B_b = 2–5			
	B = 1.75	B = 1.5	B = 1.25	B = 1	B = 1.75	B = 1.5	B = 1.25	B = 1
Fields of excavation difficulty class I, $H_p \le 200$ m								
5–25.5	≤ 200	≤ 180	≤ 170	≤ 150	≤ 200	≤ 180	≤ 150	≤ 130
30–61.2	≤ 200	≤ 180	≤ 170	≤ 150	≤ 200	≤ 190	≤ 170	≤ 140
Fields of excavation difficulty class II, $200 < H_p \le 320$ m								
5	≤ 280	≤ 240	≤ 220	≤ 200	≤ 270	≤ 230	≤ 200	≤ 170
10–25.5	≤ 290	≤ 260	≤ 240	≤ 220	≤ 290	≤ 260	≤ 230	≤ 200
30–61.2	≤ 320	≤ 280	≤ 250	≤ 230	≤ 320	≤ 280	≤ 240	≤ 210
Fields of excavation difficulty class III,$320 < H_p \le 500$ m								
5	≤ 460	≤ 410	≤ 370	≤ 350	≤ 430	≤ 370	≤ 330	≤ 280
10–25.5	≤ 490	≤ 450	≤ 410	≤ 380	≤ 470	≤ 410	≤ 360	≤ 320
30–61.2	≤ 500	≤ 460	≤ 420	≤ 390	≤ 490	≤ 420	≤ 370	≤ 330
Fields of excavation difficulty class IV, $500 < H_p \le 700$ m								
5	≤ 630	≤ 580	≤ 540	≤ 500	≤ 600	≤ 520	≤ 480	≤ 440
10–25.5	≤ 690	≤ 620	≤ 560	≤ 510	≤ 680	≤ 600	≤ 540	≤ 490
30–61.2	≤ 700	≤ 640	≤ 590	≤ 550	≤ 690	≤ 610	≤ 550	≤ 500
Fields of excavation difficulty class V, $H_p > 700$ m								
5	> 630	> 580	> 540	> 500	> 600	> 520	> 480	> 440
10–25.5	> 690	> 620	> 560	> 510	> 680	> 600	> 540	> 490
30–61.2	> 700	> 640	> 590	> 550	> 690	> 610	> 550	> 500

Having assumed that under the most adverse conditions pit depth H_p will correspond to this boundary condition and the least costly equipment complex, the optimal regions of the investigated parameters were forecasted.

Research results. As an illustration of the given methodology, by way of example, fig. 1 presents the dependences reflecting the influence of pit depth on the electric excavator bucket capacity and dump trucks loading capacity in the estimated conditions.

It can be seen from the graphs that with pit depth (and hence dimensions) growth, the operating parameters of the mining transport must be larger. Excavator bucket capacity and the associated dump truck loading capacity grow nonlinearly with the growth of the mine's depth. It is due to mining production costs which, first, depend on excavation difficulty, second, on machine capacity, third, on machine type, model and combination in a set. Meanwhile, these costs being included in ore value indicator and market inflationary practices expressed as a varying discount rate can shift rational parameters of equipment along the pit depth.

Rational uses of equipment sets based on the application of electric and hydraulic excavators with the corresponding bucket capacity which have been obtain this way have been combined in tables 2 and 3 and in fig. 2 (L_p – the length of the pit over the ground surface, m; B_p – the width of the pit over the ground surface, m).

Table 3. Rational uses of the equipment complexes with hydraulic excavators

Таблица 3. Области рационального применения комплексов оборудования с гидравлическими экскаваторами

Excavator bucket capacity E_b, m^3	Ore pit depth H_p', m							
	L_p/B_b = 1–2				L_p/B_b = 2–5			
	B = 1.75	B = 1.5	B = 1.25	B = 1	B = 1.75	B = 1.5	B = 1.25	B = 1
Fields of excavation difficulty class I, $H_p \le 200$ m								
5–42	≤ 200	≤ 180	≤ 170	≤ 150	≤ 200	≤ 170	≤ 140	≤ 130
Fields of excavation difficulty class II, $200 < H_p \le 320$ m								
5–7	≤ 310	≤ 270	≤ 240	≤ 220	≤ 310	≤ 260	≤ 220	≤ 200
10–42	≤ 320	≤ 280	≤ 240	≤ 220	≤ 320	≤ 270	≤ 230	≤ 200
Fields of excavation difficulty class III,$320 < H_p \le 500$ m								
5–7	≤ 490	≤ 460	≤ 410	≤ 380	≤ 490	≤ 420	≤ 370	≤ 320
10–42	≤ 500	≤ 480	≤ 430	≤ 390	≤ 500	≤ 440	≤ 380	≤ 340
Fields of excavation difficulty class IV, $500 < H_p \le 700$ m								
5–7	≤ 690	≤ 630	≤ 580	≤ 540	≤ 680	≤ 590	≤ 520	≤ 500
10–42	≤ 700	≤ 640	≤ 590	≤ 550	≤ 700	≤ 610	≤ 540	≤ 500
Fields of excavation difficulty class V, $H_p > 700$ m								
5–7	> 690	> 630	> 580	> 540	> 680	> 590	> 520	> 500
10–42	> 700	> 640	> 590	> 550	> 700	> 610	> 540	> 500

In order to determine the rational uses of equipment, some possible pit variants have been modeled with the account of filed development difficulty, and planform depth and dimensions. A field of competition has been formed for the main variants of drilling rigs, excavators, dump trucks and bulldozers, which are commercially available.

Costs, which considered both operating expenses and investment for every single unit of equipment when calculating *NPV* and *IRR*, were determined using count-up and predicting their dynamics with lifetime extension.

The values of pit depth in tables 2 and 3 correspond to the basic discount rate E_{co} = 10%. If E_{co} differs from the basic value then pit depth should be calculated by formulae:

$$H_p = H_p' K_{eb},$$

$$K_{eb} = Y' / 100 - Y / 100,$$

where H_p' – pit depth under discount rate E_{co} = 10% according to tables 2 and 3, m; K_{eb} – coefficient for pit depth calculation under discount rate E_{co} > 10% or E_{co} < 10%; Y and Y' – coefficients accounting for the discount rate and ore value when calculating pit depth (Y' under E_{co} = 10%, and Y under E_{co} > 10% or E_{co} < 10% in accordance with graphs at fig. 3).

In article [12] the conditions of rational reduction in the capacity of mining transport have been shown when developing deep pits or their intermediate stages. Together with that in order to try previously introduced data, at fig. 3 the results of pit development variants justification have been presented for Vostochny pit of Olympiadinsky goldfield which has a round form on a plan.

In this case pit borders have been established because of the mining transport parameters influence on the parameters of development system elements and ore value. Up to the project depth of 600 m (variant 2) it is advisable to mine using the complexes of equipment based on the excavators with 10–15 m3 bucket capacity. With mean capacity of a bucket increased up to 20–35 m^3, together with the increased power and economic efficiency of a complex in general, it is possible to come down to the depth of 710 m (according to variant 4 in accordance with the data from table 2).

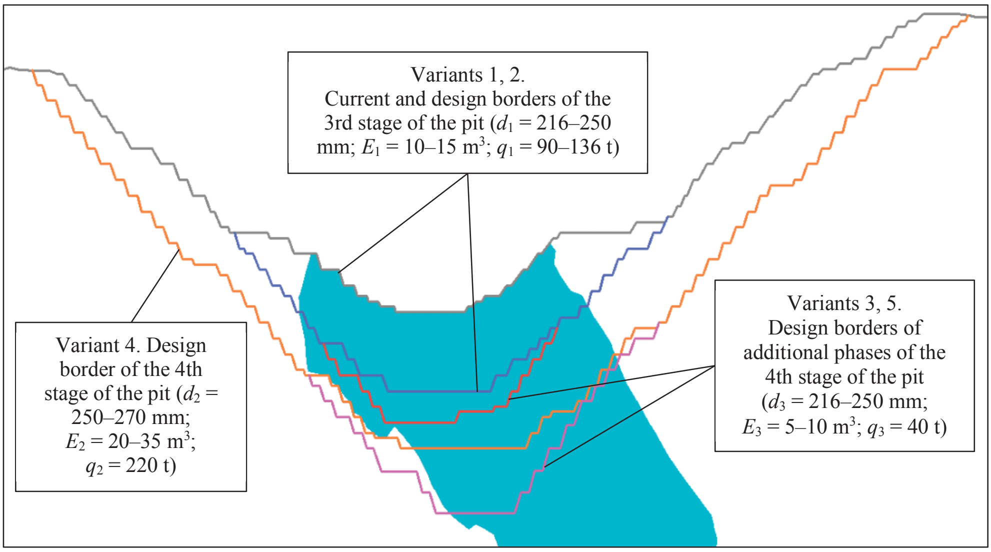

Fig. 3. Rational dynamics of the mining and conveyor equipment parameters on Vostochny pit depth:
1 – 450 m; 2 – 600 m; 3 – 660 m; 4 – 710 m; 5 – 830 m; d_1, d_2, d_3 is a diameter of a drilling bit; E_1, E_2, E_3 – the excavator bucket capacity; q_1, q_2, q_3 is dumptruck loading capacity

Рис. 3. Рациональная динамика параметров горнотранспортного оборудования по глубине карьера «Восточный»:
1 – 450 м; 2 – 600 м; 3 – 660 м; 4 – 710 м; 5 – 830 м; d_1, d_2, d_3 – диаметр долота бурового станка; E_1, E_2, E_3 – вместимость ковша экскаватора; q_1, q_2, q_3 – грузоподъемность автосамосвала

Further application of excavators and articulated dump trucks with reduced bucket capacity and loading capacity (variants 3 and 5) allows to reach the depth of 660 and 830 m. Minimum width of such dump trucks together with their ability to cope with high haulage slopes make it possible to distinguish between two mining-engineering stages in mining, reduce and defer significant part of stripping activity to later periods, and increase the volume of the produced minerals and their value.

Summary. The above states testifies to the fact that the parameters of mining transport and ore pit depth are interconnected with a number of factors: first, physical and technical characteristics of the mined rock and their occurrence conditions, second, equipment types and workflow organization and technologies, third, price volatility and inflation processes in the world market.

To generally estimate these constituents, the fields have been classified according to the relative difficulty of excavation, while the produced ore reserves have been classified according to their value. Five classes of fields have been singled out according to excavation difficulty up to pit depth of 200 m, 320 m, 500 m, 700 m, and more than 700 m.

For each field class ore reserves division has been established by value within the following limits: $B < 1$; $1 < B < 1.25$; $1.25 < B < 1.5$; $1.5 < B < 1.75$; $B > 1.75$. Considering this, rational uses of equipment complexes with electric and hydraulic excavators have been determined; it has been stated than with pit planform depth and dimensions growth it is advisable to apply more powerful and less costly equipment. Under the base discount rate of 10%, the ultimate pit depth for each class can vary up to 20–25%. This tendency is true under normal advance of mining, while at the stage of developing a deep and power pit it is advisable to transfer to equipment with smaller dimensions because of the reduced working zone.

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Экономико-технологические аспекты взаимосвязи глубины рудных карьеров и параметров горнотранспортного оборудования

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Реферат

Введение. *В статье приведены результаты исследований по обоснованию глубины рудного карьера в увязке с параметрами горнотранспортного оборудования, представленного на рынке России.*
Теория исследований. *Рассмотрены особенности современного состояния и дальнейшего развития глубоких карьеров. Дана классификация месторождений по относительной трудности разработки в зависимости от физико-технических характеристик пород, условий их залегания и*

жесткости климата, а также извлекаемых запасов руды в зависимости от ее ценности. Предложены показатели для совместного обоснования трудности разработки, глубины рудного карьера, параметров комплексов горнотранспортного оборудования и установлены области их оптимальных значений.

Результаты и выводы. *Получены зависимости, позволяющие оперативно определять вместимость ковша экскаватора, грузоподъемность автосамосвала и обосновывать глубину карьера с учетом ценности руды. Установлено, что при открытой разработке месторождения соответствующего класса трудности разработки динамика затрат с глубиной обусловлена увеличением мощности, производительности и энерговооруженности буровых станков, экскаваторов, автосамосвалов, бульдозеров и имеет возрастающий нелинейный характер. Выделены области рационального применения комплексов горнотранспортного оборудования, основанных на электрических и гидравлических экскаваторах. Оценены причины вероятного их изменения. Результаты исследований апробированы при проектировании самого крупного золоторудного карьера «Восточный» в России по разработке Олимпиадинского золоторудного месторождения.*

Ключевые слова: *глубина рудного карьера; вместимость ковша экскаватора; грузоподъемность автосамосвала; прибыль; чистый дисконтированный доход; внутренняя норма доходности; ценность руд.*

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