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Research paper

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Behaviour pattern of rock mass haulage energy intensity in deep pits

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Abstract
A significant portion of mineral deposits developed by open-pit mining is opened to the full depth by road transport ramps without the use of combined transport. In most cases, this is dictated by the high rate of a pit deepening and multi-stage development. In this study, the energy intensity of rock mass (RoM) haulage from the working zone of a pit to the surface is considered at several hierarchical levels. Mineframe software was used to study 3D-models of open pits with different slope angles in order to test the method of analytical calculation of a pit volume that allowed ensuring accuracy under a wide range of mining conditions. The findings of the research are as follows: with an increase in the pit bottom diameter, the zone of stabilization of rock mass lifting (haulage) height shifts to greater target depths. An increase in the pit slope angles entails shifting the weighted average height to deeper elevations. By increasing the pit target depth, combined modes of transport become more economical in comparison with dump trucks due to an increase in the total volume of rock mass. Depending on the comparison purpose, it was proposed to use different types of energy intensity. For a broad estimation of the rationality of the pair "scheme of opening – mode of transport" for open pits, the ratio of potential energy intensities of rock mass haulage of a considered option of a pit opening and its basic option without transport berms was used. The ratio of potential energy intensities as a function of a pit depth was determined. The values of total energy intensity of rock mass haulage from a pit to the surface were also established.

Keywords
energy intensity, open pit haulage system, deep pit, opening scheme, transport berm, pit dump trucks, slope angle

Acknowledgments
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ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Закономерности изменения энергоемкости транспортирования горной массы транспортом глубоких карьеров

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Аннотация
Значительная часть месторождений полезных ископаемых, разрабатываемых открытым способом, вскрывается автомобильными транспортными съездами на всю глубину без использования комбинированного транспорта. В большинстве случаев это связано с высокой скоростью снижения уровня горных работ и многоэтапной разработкой. Методы исследований энергоемкости транспортирования горной массы из рабочей зоны карьера на поверхность рассматриваются в несколько иерархических уровней. Для исследования 3D-моделей карьеров с различными углами откоса использовано программное обеспечение Mineframe с целью забазировать методику аналитического расчета объема карьера, что позволило обеспечить точность при широком охвате диапазона горнотехнических условий. При увеличении диаметра дна карьера зона стабилизации высоты подъема смещается к большим конеч-

ным глубинам, увеличение угла откоса бортов карьера влечет за собой смещение средневзвешенной высоты в глубину, с ростом конечной глубины карьера комбинированные виды транспорта становятся более экономичными в сравнении с автомобильным за счет увеличения суммарного объема горной массы. В зависимости от цели сравнения предложено использовать различные виды энергоемкости, для укрупненной оценки рациональности пары «схемы вскрытия – вид транспорта» для карьеров возможно использовать отношение потенциальных энергоемкостей перемещения горной массы рассматриваемого варианта вскрытия карьера и его базовой версии без транспортных берм, установлены закономерности изменения отношения потенциальных энергоемкостей от глубины карьера, определены значения полной энергоемкости транспортирования горной массы из карьера до поверхности комбинированными видами транспорта.

Ключевые слова
энергоёмкость, транспортная система карьера, глубокий карьер, схема вскрытия, транспортная берма, карьерные автосамосвалы, угол откоса бортов

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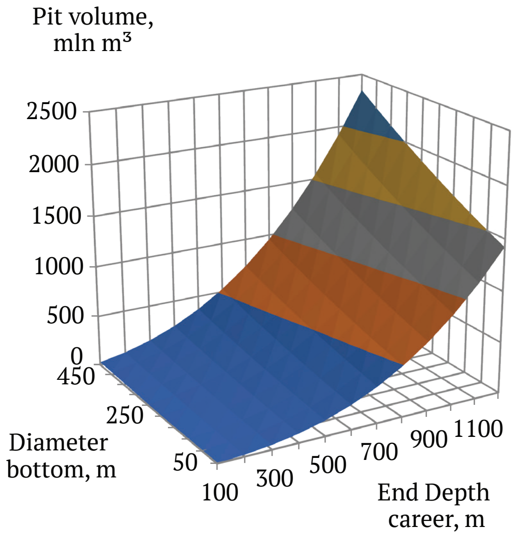
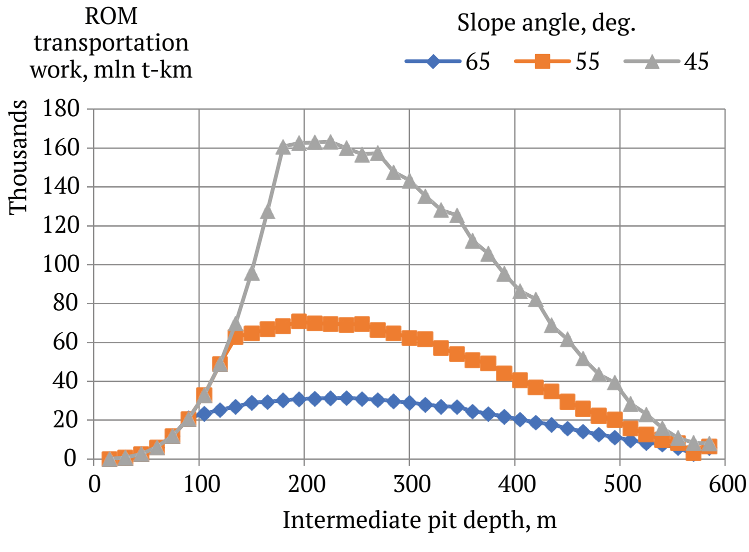
Introduction

A significant portion of mineral deposits developed by open-pit mining is opened to the full depth by road transport ramps without the use of combined transport. As a rule, this is dictated by the high rate of a pit deepening, multi-stage development (up to 5–6 stages with a cutback at full height at each stage) that does not allow more economical, but capital-intensive modes of transport to be implemented. At the same time, the effective development of these deposits with the fullest possible extraction of reserves is an urgent task [1, 2].

The volume of rock mass within the envelope of a pit depends significantly on its depth and size in plan view, and, with an increase in its depth, the volume increases parabolically (Fig. 1). At the same time, the distribution of these volumes by bench is uneven. Deepening leads to a decrease in the volume of each underlying horizon, while the distance of haulage increases [3]. The final figures of haulage work while developing a deposit by a deep round pit is described by an ascending-and-descending curve. For instance, Fig. 1, *b* shows a graph built without taking into account annual smoothing production volumes. It can be seen that the peak value and intensity of the change in the tonne-km work significantly depend on the slope angles of the pit walls.



a



b

Fig. 1. Dependence of the volume of rock mass and haulage work within a round-shaped pit envelope on the size of the bottom, target depth, and slope angle of the walls:
a – dependence of the volume of rock mass within a round-shaped pit envelope;
b – the haulage work depending on a pit depth at the target depth of – 585 m

The way to manage the shape of a pit walls in a final pit envelope, in order to achieve significant slope angles is to optimize the parameters of transport (haulage) lines:

– use of narrow transport berms, including t single-lane roads with separation of the laden and unladen vehicle traffics;

– use of increased road gradients;

– use of appropriate modes of transport located on benches without transport berms (high incline conveyor, skip hoist, freight suspended ropeway, etc.), etc.

In order to compare different schemes of opening of mineral deposits in an open-pit with different modes of transport, certain criteria need to be defined. One such a criterion can be the energy intensity of hauling the entire volume of rock mass from a pit.

The approach which uses energy intensity as an indicator or criterion for evaluating open-pit mining processes or mining machines is used in a number of studies [4–7]. This indicates both the universality of this method and the relevance of the problem under consideration. The topic of energy efficiency has been pressing for the last 20 years. For example, the paper "Substantiating systems of open-pit mining equipment in the context of specific costs" [8] describes the energy efficiency of equipment in coal mines. The study "Energy consumption in open-pit mining operations relying on reduced energy consumption for haulage using in-pit crusher systems" [9] investigates energy efficiency in haulage with the use of in-pit crushing systems. "Smart energy management: a comparative study of energy consumption forecasting algorithms for an experimental open-pit mine" [10] is a paper which reviews the problem of smart energy efficiency management. In the study "Structure of energy consumption and improving open-pit dump truck efficiency" [11], increasing energy efficiency through reducing energy consumption is considered. The paper "An integrated model of an open-pit coal mine: improving energy efficiency decisions" [12] describes an integrated model of a coal mine. The paper "Bulk material transportation system in open pit mines with improved energy efficiency" [13] describes the increase in energy efficiency of bulk material transportation. Ageneralized approach to assessing transport systems on the whole and the energy efficiency of individual vehicles should be combined.

Research tasks and objectives

1) to structure the energy intensity of rock mass (RoM) haulage, applicable to compare the efficiency of transport modes and opening schemes, by hierarchical level;

2) to establish patterns of change in the relative energy intensity of rock mass haulage from a pit to the surface depending on the parameters of a pit;

3) to determine the energy intensity of rock mass haulage by different modes of transport when opening the working zone by truck transport.

Research techniques

In this study, the energy intensity of rock mass haulage from the working zone of a pit to the surface is considered in several hierarchical levels (Table 1).

Since the study is aimed at identifying general patterns, for simplicity the calculation of the volume of rock mass within a pit envelope is performed as for an inverted truncated cone, the generatrix slope of which corresponds to the average slope angle of the pit walls.

To a certain extent, when searching for a rational scheme of opening and an appropriate mode of transport, an open pit that has no transport berms can be considered as the ultimate optimized option. Only bench sloping (working berms) is implemented on its walls, and the wall slope angles are selected to maintain wall stability. We will conventionally call such pit a "basic" option. A number of 3D models of pits with slope angles of 35, 45, 55 and 65°, on the target envelopes (walls) of which transport berms were positioned, were studied. The simulation was carried out in Mineframe software package [14] for a number of open pit options, in order to test the method of analytical calculation of a pit volume [15], which allowed accuracy to be achieved under a wide range of mining conditions.

The working berm was assumed to be 15 m wide. The width of transport berms was taken as different in accordance with the rational type of dump trucks for a particular size of a pit (taking into account a pit dimensions in plan and depth) which determines the production capacity. The range of variation was as follows:

– for small pits, the width of berms of 24.5 m is designed for 60–90 ton-payload dump trucks;

– for large pits, the width of berms of 34 m is designed for 130–160 ton-payload dump trucks.

Fig. 2 shows the results. They demonstrate that the construction of spiral ramp berms leads to a decrease in the wall slope angles by 2–3° for small basic angles and by 5–7° for large basic angles. The data processing enabled the dependences of the slope angle on the pit depth and the overall pit slope angle (Table 2) to be determined. They were used in further calculations.

In order to cover a set of pits in terms of the stability of walls. the following basic overall slope angles were taken: 35°, 45°, 55°, 65°.

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Table 1

Hierarchical levels of hauling energy intensity research

	Level of energy intensity consideration	Expression for estimation	Significance
1	Energy intensity of haulage in units of potential energy (conservative forces only), taking into account the volume for pushback for the placement of haulage lines	$\frac{\Delta E_p}{\Delta E_{p0}}$	Effect of pushback for the placement of haulage lines, taking into account their parameters, on the total energy intensity (as a rule, produces the main effect on the total energy intensity)
2	Energy intensity of haulage in units of physical work of external (in relation to vehicles) conservative forces and external dissipative forces	$\frac{A_{(T1)}}{A_{(T2)}} = \frac{\Delta E_{p(T1)} + A_{d(T1)}}{\Delta E_{p(T2)} + A_{d(T2)}}$	When comparing modes of transport: along with the effect of the haulage lines parameters, the energy efficiency of a drive (propelling unit) of a particular mode/modification of transport is taken into account
3	Energy intensity of haulage taking into account the energy carrier indicators	$\frac{Q}{E_{po}} = \frac{(\Delta E_p + A_d)q}{\Delta E_{p0}}$	1. For a particular mode of transport: selection of the optimal shape of the walls of pushbacks and an ultimate pit, determination of rational parameters of openings (slope and width of transport berms, etc.)
		$\frac{Q_{(T1)}}{Q_{(T2)}} = \frac{(\Delta E_{p(T1)} + A_{d(T1)})q_{T1}}{(\Delta E_{p(T2)} + A_{d(T2)})q_{T2}}$	2. When comparing modes of transport: the selection of energy-efficient mode of transport, taking into account the energy carrier indicators (fuel calorific value, coefficient of efficiency of electricity generation and transmission, etc.) and the coefficient of efficiency of the power plant of vehicles

Notes: ΔE_p, ΔE_{p0} are energy intensities of rock mass lifting (difference of the mass potential energies on the surface and in situ in a pit) for an open pit with haulage lines (ΔE_p) and the basic pit option (ΔE_{p0}), respectively; A_d is work against dissipative forces when hauling the rock mass; *T*1, *T*2 are modes/modifications of transport 1 and 2, respectively; *Q* is total energy inputs for rock mass haulage; *q* is specific energy intensity of generation and transmission of a unit of energy by a power plant to a vehicle's engine (for example, the lower calorific value of fuel, taking into account the coefficient of efficiency of the internal combustion engine and the transmission).

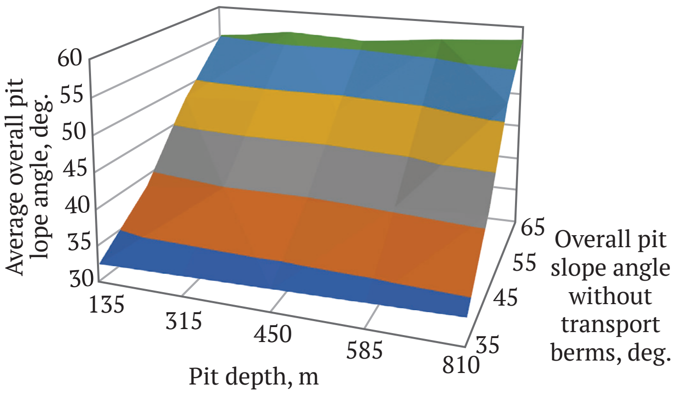

Fig. 2. Changing slope angle of a round-shaped pit when constructing transport berms for spiral ramps on the walls

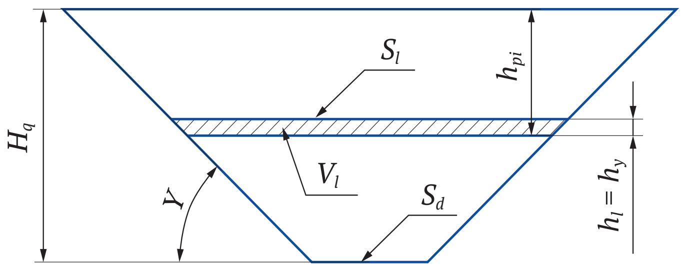

Fig. 3. Scheme for determining the volume of layers to be excavated within a pit envelope: S_l is layer area, m²; S_d is bottom area, m²; V_l is layer volume, m³; h_l is layer height, m; h_y is bench heigh, m; h_{pi} height from the top elevation of a pit (daylight surface) to the bottom elevation of a layer, m; *Y* is overall pit slope angle, deg; H_q is pit wall height

Table 2

Dependencies of slope angle on pit depth (H_k)

Параметры	Overall pit slope angle			
	35°	45°	55°	65°
Dependence of pit slope angle on pit depth y	$0.0018H_k + 32.168$	$0.0035H_k + 38.325$	$0.0052H_k + 46.898$	$0.004H_k + 54.771$
Confidence R^2	0.9967	0.884	0.7647	0.8848

Let us define the theoretical energy intensity as the energy spent for lifting the whole volume of a rock mass within a pit envelope to the surface, described by the change in the potential energy of each elementary volume between the positions "on the surface" and "in situ". In this case, the calculation shall be performed layer-by-layer, since the material moving in the horizontal plane does not lead to a change in energy intensity taking into account the accepted assumptions (Fig. 3).

Correspondingly, the energy intensity of rock mass haulage from a pit envelope:

$$\Delta E_p = \sum V_{li} \rho h_{pi} g = \int_0^{H_k} g \rho h_{pi} S_l dh_{pi}, \qquad (1)$$

where V_{li} is volume of the i-th layer (horizon) within a pit envelope, m^3; h_{pi} is height from the bottom of the i-th layer to the surface of the pit (height of rock mass lifting), m; g is free fall acceleration (9.81), m/s^2; ρ is density of rock mass in a pillar, т/m^3.

When passing to an integral, a layer height decreases to an infinitesimal value, so the areas of the bottom and the top of the truncated cone, which represents each layer, can be considered to be equal. The corresponding area, m^2, is defined as follows:

$$S_l = S_d + 2\sqrt{\pi s_d} H_k \, ctg\,\gamma - 2\sqrt{\pi s_d} h_{pi} \, ctg\,\gamma + \\ + \pi H_k^2 ctg^2\gamma - 2\pi H_k h_{pi} ctg^2\gamma + \pi h_{pi}^2 ctg^2\gamma, \qquad (2)$$

where S_d is the area of the bottom of a pit, m^2; γ is the average overall pit slope angle, deg; H_k is target depth of a pit, m.

Correspondingly, the formula for determining E_p can be expressed as:

$$\Delta E_p = \int_0^{H_k} \rho g (S_d + 2\sqrt{\pi s_d} H_k ctg\,\gamma - 2\sqrt{\pi s_d} h_{pi} ctg\,\gamma + \\ + \pi H_k^2 ctg^2\gamma - 2\pi H_k h_{pi} ctg^2\gamma + \pi h_{pi}^2 ctg^2\gamma) dh_{pi}. \qquad (3)$$

After all transformations and integration, the formula takes the following form:

$$\Delta E_p = \rho g \left(\frac{\pi ctg^2\gamma}{12} H_k^4 + \frac{\sqrt{\pi S_d} ctg\,\gamma}{3} H_k^3 + \frac{S_d}{2} H_k^2 \right). \qquad (4)$$

Research Findings

As already mentioned above, the energy intensity of rock mass haulage is determined by two main factors: the distribution of volumes within a pit envelope; and the increase in energy consumption for haulage with extraction deepening. Therefore, in order to explain the patterns of changes in the energy intensity when changing the parameters of open pits, it is important to identify their influence on the location of the "center of mass" of the total volume of rock mass within a pit envelope. It can be seen in Fig. 4, a that, at a bottom diameter of 100 m, with increasing the target depth of a pit above 500–600 m, the average weighted height of rock mass lifting stabilizes at 26–28 % of the target depth, and, at the depth less than 200 m, the height increases sharply, becoming practically equal to the full depth of a pit. As the pit bottom diameter increases, the lifting

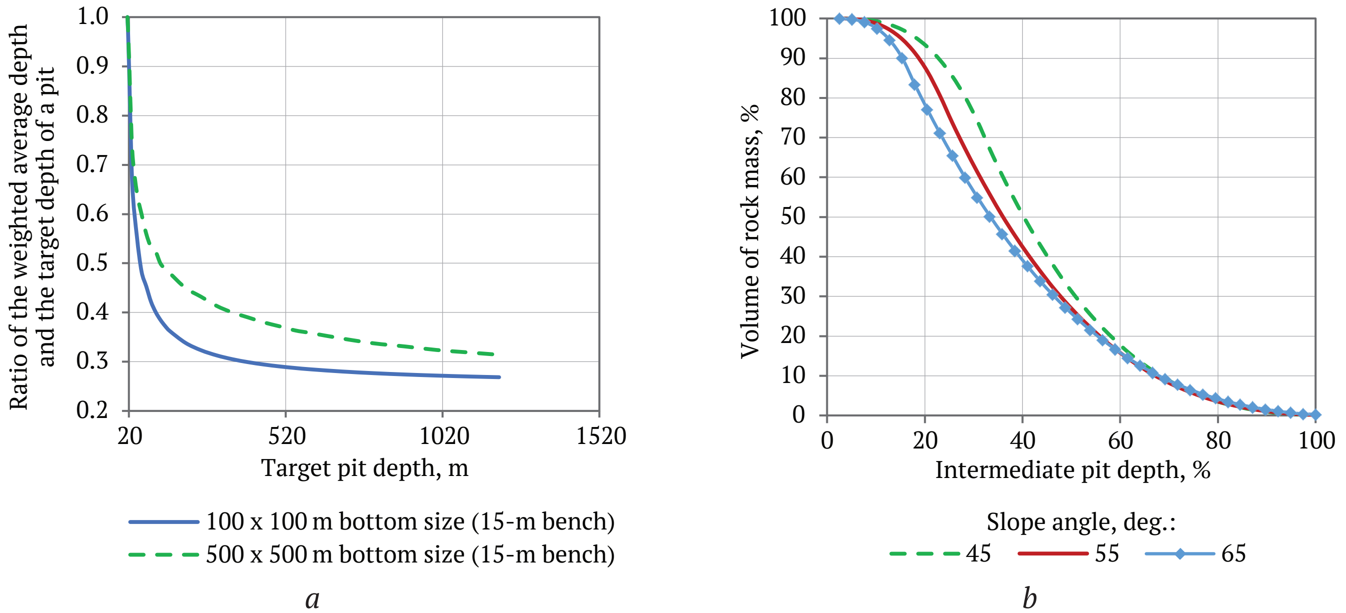

Fig. 4. Pattern of changes in the position of the "center of mass" of the rock mass volume within a pit envelope depending on its parameters:
a – ratio of the average weighted (by the volume of excavated rock mass) depth of a pit to the target depth of a pit;
b – reciprocal cumulative graph of the volume of rock mass in a pit envelope as a function of a pit depth

height stabilization zone shifts to greater target depth values. Increasing the pit slope angle entails a shift of the average weighted height towards greater depths (Fig. 4, *b*).

Calculations showed that the energy intensity of rock mass haulage, based on the difference in the potential energy (see Table 1, p. 1), characterizes the mining and geological conditions and the scheme of opening as a whole. Fig. 5 shows that its increase with the depth of a pit is generally similar to the increase in the volume of pit space. However, as the analysis showed, this is more intense due to increasing energy consumption with depth. Increasing the slope angles naturally leads to decreasing the rock volumes and, consequently, the total energy costs, while increasing the diameter of the bottom leads to the costs increase.

A convenient way to compare alternative opening schemes is to calculate relative energy intensity, as equal to the ratio of the energy intensity of hauling the whole volume of the rock mass within a pit with the considered opening scheme ΔE_p to the energy intensity for a pit without opening berms and ramps ΔE_{p0}. It makes it possible to estimate the contribution of opening berms and ramps to the increase in the volumes and their distribution by depth. Let us consider the results of the calculations in more detail.

Fig. 6 shows that the curves of the dependences of the relative energy intensity on the target depth of a pit have maximums, corresponding to the greatest negative impact of the placement of transport berms on a pit wall cutback. This pattern is "natural", arising from geometry, so these groups of pits should be subject to mandatory optimization. The decrease in relative energy intensity with further increase in depth can be explained by a decrease in the proportion of wall cutback in the geometric volume of the pit space and a smaller decrease in the slope angles of a pit due to the distribution of transport berms over the increasing perimeter of the outline of a pit. For the same reasons, the specific energy intensity decreases as the size of a pit bottom increases.

Fig. 7 shows that with growth of the basic pit slope angle (without transport berms), which were taken in the study as the limiting stable slope angle, the relative energy intensity increases at all depths. However, the character of this growth changes (see Fig. 7, *b*): at low depths the intensity of growth decreases; at depths of 400–500 m the graph is almost straight, and then it curves, approaching the parabolic form.

Pit bottom diameter has a significant impact on the relative energy intensity. With a large bottom diameter, the relative energy intensity is generally lower than in the case of a small diameter (Fig. 8). Moreover, if at small bottom sizes, the maximum energy intensity is observed at a depth of the pit of 100–500 m, then at an extensive bottom the intensity shifts to depths of 500–900 m. Consequently, the greatest negative impact from the wall cutback of a pit for the placement of haulage lines on them is observed for pits with relatively small size of the bottom, 50–100 m in diameter at a depth of 100–500 m.

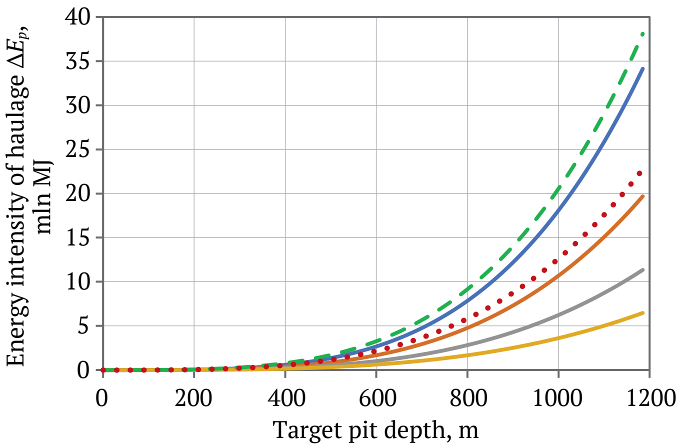

Fig. 5. Theoretical energy intensity of the haulage of the rock mass within a pit envelope |to the surface ΔE_p

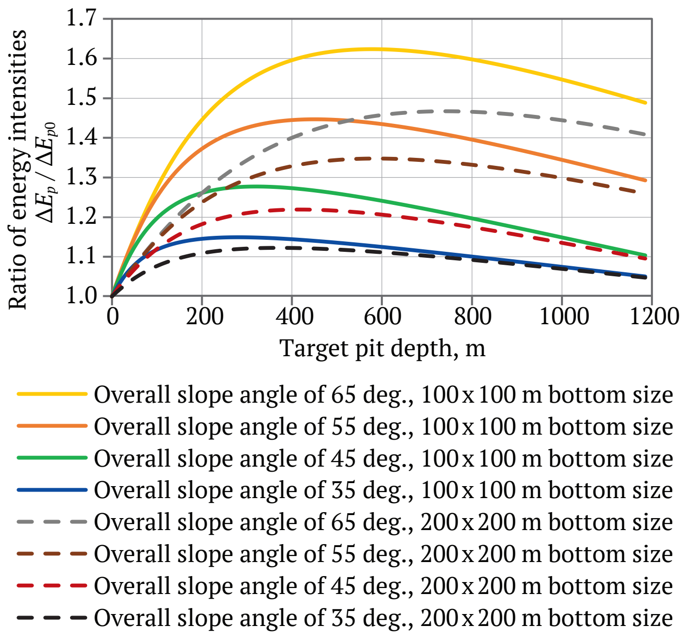

Fig. 6. Changing the relative theoretical energy intensity of rock mass haulage from a pit with depth at different parameters of a pit

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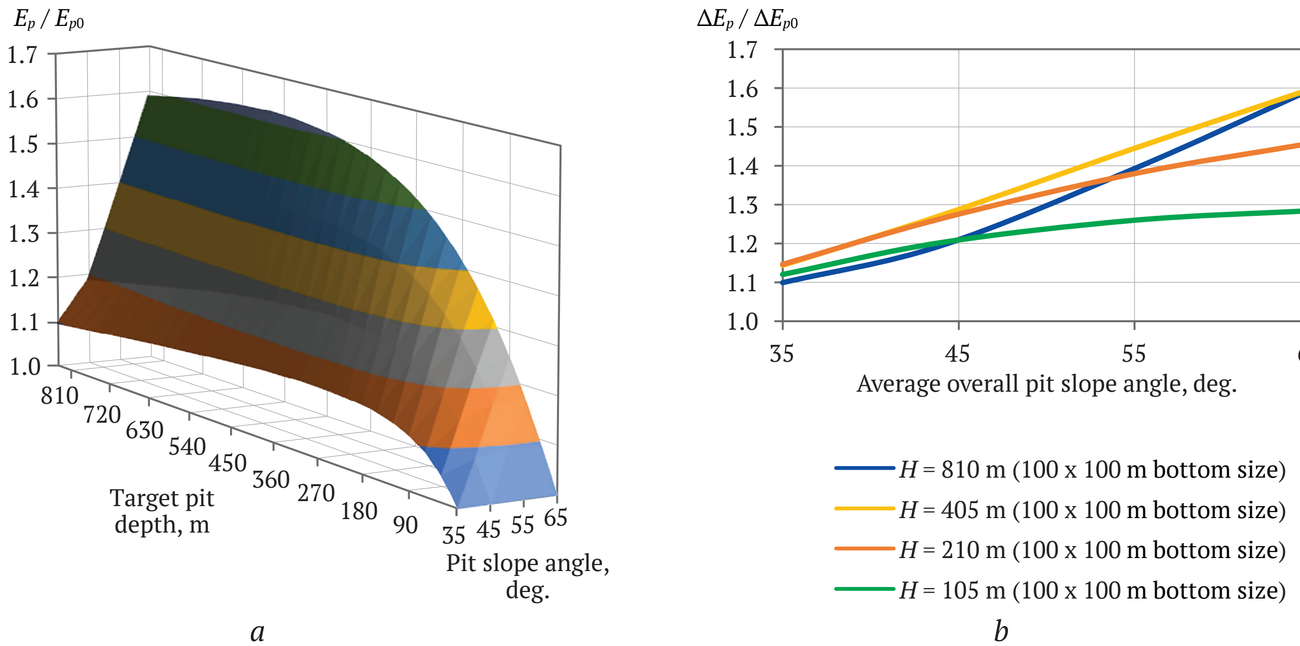

Fig. 7. The ratio of energy intensities $\Delta E_p / \Delta E_{p0}$ depending on the overall slope angle of a basic pit (not taking into account transport berms):
a – summary three-dimensional graph; *b* – graphs for specific depths

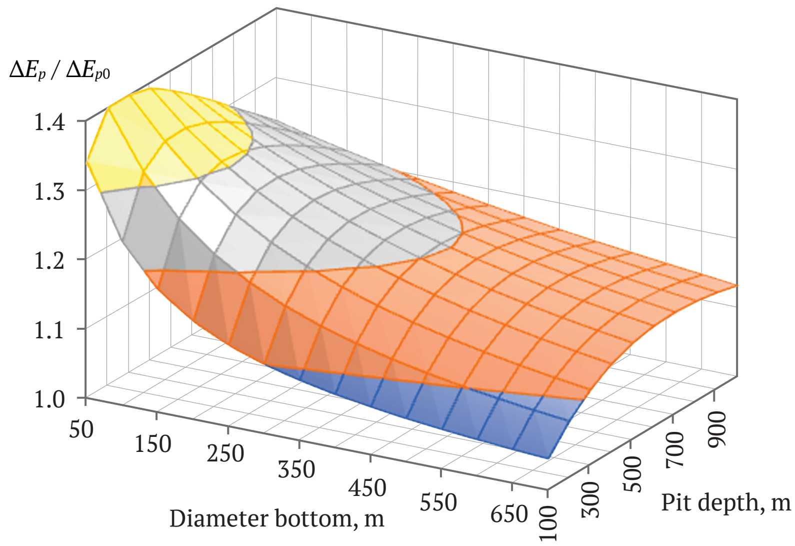

Fig. 8. The ratio of energy intensities $\Delta E_p / \Delta E_{p0}$ depending on the pit depth and diameter of its bottom for the option of the basic pit with an average slope angle of 45°

The patterns described above refer to the theoretical energy intensity. In practice, it is markedly influenced by the mode of transport used, characterized by specific energy consumption. In order to bring different modes of transport with different energy carriers (diesel fuel, electricity) to a comparable type of energy intensity, the following must be used (Table 3):

– the calculated work of conservative and dissipative forces on a vehicle engine;

– the energy of the primary fuel by its calorific value, at the place of its generation (diesel engine of autonomous vehicles or a power plant).

With regards to the second option, the study [6] suggests and describes the method of reducing the energy intensity of a transport mode to the amount of consumed fuel equivalent in g of f.e./(t·m), suitable for practical calculations in natural terms. However, given that it is more convenient to operate with energy units within the framework of this study, including for the transition to dimensionless relative units, Table 3 shows the results of the calculations based on: traction calculation, transmission efficiency calculation, averaged reference efficiency of engines, lower calorific value of fuel, and calculation of the losses in power lines. For electrified modes of transport (rail and conveyor), a scheme with electricity generation at a gas turbine mini thermal power plant located in the immediate vicinity of a pit was adopted.

Note that these indicators are averaged and depend on specific mining conditions (weighted average slope of the route, haulage distance, configuration of haulage lines, etc.).

The capabilities of the approach under consideration were tested by comparing the combined modes of transport: truck+rail and truck+conveyor. The slope angle of a pit with haulage lines on the walls was taken into account, as well as the specific energy intensity of hauling depending on the height of the rock mass lifting (the pit depth). For the sake of convenience, the results of the calculations are given in the form of the ratio of energy intensities (Fig. 9): the smaller this ratio, the more economical

Table 3

Specific energy intensity of generation and transmission of a unit of energy by a power plant to a vehicle's engine

Mode of transport	Specific energy intensity by mode of transport[1]	
	MJ/MJ (work of forces on the wheels of a vehicle)	MJ/MJ (taking into account the heat of combustion, the efficiency of PP and the transmission from the power line to a vehicle)
Ratio to the energy intensity indicator according to Table 1.	$A / \Delta E_p$	$Q / \Delta E_p$
Dump trucks	3.28	9.89
ЖRail / Trucks + Rail[2]	2.01 / 2.52–2.64	6.89 / 8.09–8.39
Conveyor / Trucks + Conveyor[2]	1.88 / 2.44–2.16[3]	5.98 / 7.37–6.53[3]

[1] In the numerator, the initial consumption of the energy carrier is converted into fuel equivalent.
[2] In the range of pit depths of 200-1000m, the height of the working zone of dump trucks is accepted: in case of rail transport, 80–400 m, in case of conveyor transport, 80–150 m.
[3] Taking into account coarse crushing; PP – power plant.

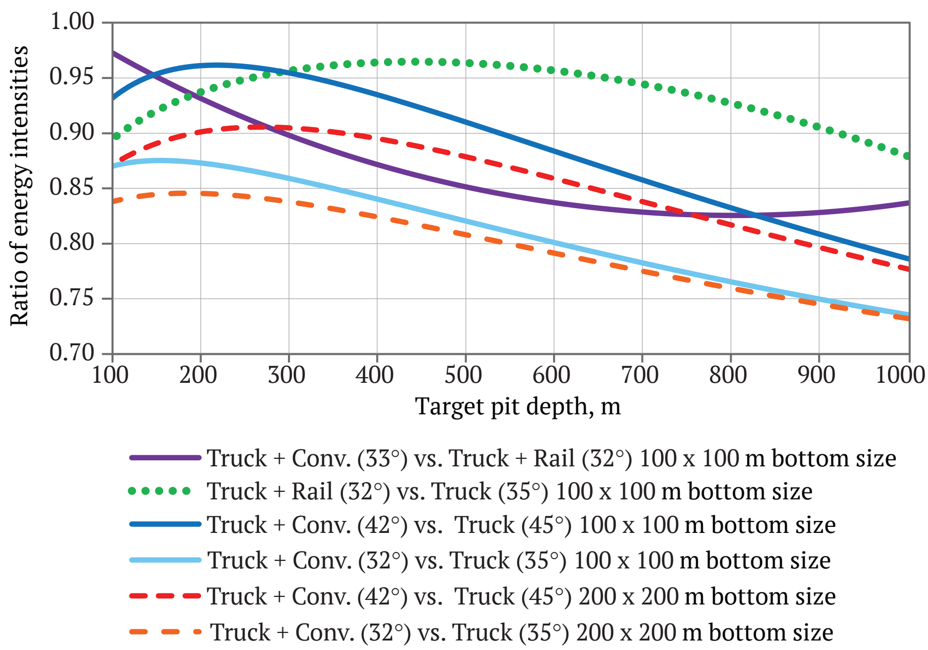

Fig. 9. The ratio of total energy intensities (*Q*) of hauling rock mass to the surface from a pit, taking into account the heat of combustion of an initial fuel by mode of transport: Truck + Rail – Dump Trucks + Railway transport; Truck + Conv. – Dump Trucks + Conveyor transport. In parentheses, the average pit slope angle is given

the transport mode indicated in the numerator of the fraction. At the given parameters, the truck-conveyor transport mode has less energy intensity in the entire depth range as compared to the truck-rail and truck transport modes. This is achieved due to optimizing the shape of the walls and increasing their slope angle as compared to rail transport, as well as lower specific energy consumption, especially as compared to truck transport. This difference can be increased by optimizing the layout of conveyor lines on the walls of a pit [16, 17]. As a pit target depth and a pit bottom diameter increase, the combined modes of transport become more economical in comparison with dump trucks due to increasing the total volume of rock mass to be hauled.

Conclusions

1. The proposed approach is based on a universal integral indicator, which allows the energy efficiency (in units of natural values) of the options of opening schemes and modes of pit transport to be compared. This approach takes into account the decrease in the volume of extracted rock mass with depth and the increase in energy consumption for its lifting (hauling) to the surface.

Depending on the purpose of the comparison, it is proposed to use relative theoretical energy intensity, the work of conservative and dissipative forces on the drive of a vehicle, or total energy intensity taking into account the efficiency of fuel energy conversion and transmission.

2. The ratio of potential energy intensities $\Delta E_p/\Delta E_{p0}$ of rock mass haulage for a considered option of a pit opening and its basic option without transport berms can be used for the broad estimation of the rationality of the pair “scheme of opening – mode of transport” for open pits. The closer this indicator is to “1”, the more optimal the adopted design of the walls of a pit.

3. The patterns of changes in the ratio of potential energy intensities $\Delta E_p/\Delta E_{p0}$ depending on pit depth, slope angles, and the bottom diameter were established, indicating that the greatest negative impact from the wall cutback for the placement of haulage lines on them is observed in pits with relatively small size of the bottom, 0–50 m in diameter at a depth of 100–500 m.

4. The total energy intensity of rock mass haulage for deep open pits and open pits with significant size of the bottom (200 m in diameter and more) is most influenced by the energy efficiency of transport mode, while for pits less than 500 m deep with a lower bottom size m (up to 100–150 m in diameter), mainly by optimization of the shape of a pit towards its reduction (while maintaining a given volume of extracted rock mass).

5. The values of the total energy intensity of hauling rock mass from a pit to the surface by combined modes of transport were determined. It was shown that due to the higher energy efficiency of rail and conveyor transport in combination with truck transport, they were more economical when compared to truck transport alone, while truck-conveyor transport combination was more economical than truck-rail transport combination due to the shortest haulage distance.

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