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IMPROVING THE EFFICIENCY OF USING DUMP TRUCKS UNDER CONDITIONS OF CAREER AT OPEN MINING WORKS

Purpose. Increasing the efficiency of road transport by changing the structure of slopes of transport inclines in open-cast mining of mineral deposits.

Methodology. The paper uses a theoretical analysis based on the theory of the use of the acting inertia forces of a moving dump truck to overcome the elevated slopes of the traffic route. The analysis and generalization of the analytical method for solving the kinematics equations of uniformly variable (equally accelerated or equally slow) motion of dump trucks was used to confirm the theoretical results and accepted assumptions.

Findings. The paper attempts to generalize, develop and offer more complete solutions to the problems of rational use of dump trucks by using the inertia forces of a moving dump truck to overcome the elevated slopes of the career roads. There is given an analytical solution of traction and braking problems when trucks overcome the slopes of transport inclines in open field mining. It is shown that these solutions are the simplest for practical use when designing new career routes, while exploiting transport inclines of deep quarries.

Originality. Mathematical models of dynamic processes occurring during the implementation of the tangential traction force of a motorized dump truck developed on elevated slopes of career paths are developed. They differ from those known by the fact that inertia forces resulting from acceleration during the motion of a dump truck are used to overcome elevated gradients in the transport inclines of quarries. As a result of numerical simulation, the regularities of changes in the speed of movement of dump trucks with alternating horizontal and inclined road sections depending on their length and slope angles were established. This allows improving the process according to the criterion of surmounted elevated slopes of open pit transport inclines, cutting their length almost by half, reducing the time of movement of dump trucks and improving performance during transportation of rock mass.

Practical value. The results obtained in the work, presented in the form of calculation formulas, make it possible to reasonably calculate the routes of transport inclines for the open mining of mineral deposits at the quarry design stage. This ensures reduction of the size of the quarries cutback in the development of deep quarries.

Keywords: *dump truck, slope, tangential traction force, friction coefficient (adhesion), open pit mining*

Introduction. The indisputable development trend of the world mining industry in the foreseeable future is considered to be a stable orientation to the open method of mining, as providing the best economic indicators. It accounts for up to 73 % of total mining in the world (83 % in

the United States, and about 70 % in the CIS countries). Over the past 40 years, there has been a steady growth in the extraction of virtually all solid minerals by open pit mining [1]. If we take into account that as the depth of quarries grows, the share of costs for open pit transport reaches 55–60 % of the total cost of mining, it is quite obvious that the issues of developing and improving open pit mining are among the main ones for open pit mining.

Statement of the problem. The main factors determining the development of career transport are systematically worsening mining-geological and mining-technical conditions of production. It is known that the development of an open method of development is accompanied by an increase in the concentration of production, an increase in the depth and spatial dimensions of the quarries, and the distance and complexity of transportation of the rock mass. The determining factor is the depth of the quarries.

Automobile transport, as transport of the working area of the open-pit mine, is the most exposed to the effects of mining conditions that are more complex with depth. The main limitation of the use of road transport in deep quarries is still the high cost of transportation of the rock mass. In addition, career road transport is the main source of negative anthropogenic environmental impact during open pit mining.

In order to expand the field of application of automotive vehicles in deep quarries, increase its efficiency, the search for new technological schemes, as well as ways of its development and improvement, continues.

In recent years, the need for accelerated preparation of new horizons, as well as for new equipment that could operate at a higher rate of lowering mining operations, has opened up with access to new deep-seated reserves of raw materials. No less important is the extension of the service life of quarries that have reached their design depth, due to their deepening with a minimum separation of boards and an increase in the volume of overburden works.

Analysis of the recent research and publications. One of the methods for using road transport in deep quarries is the development of special zigzag roads for the export of harvested rock [2]. The need to change the traditional transport schemes for motor vehicles in open-pit mining is caused, on the one hand, by the increasing depth of the quarries, and on the other hand, it is caused by the heightened environmental situation in deep quarries, due to the large gas content of the quarry space; in some cases equipment downtime reaches 1000–1500 hours per year. One of the ways to solve this problem is to increase the capacity of mining dump trucks, which allows reducing the number of cars [3].

But due constructive solutions to improve of the cars design [4] this problem can't be fully solved. Based on this, some researchers believe that the load on vehicles should be reduced and redistributed between it and the railway [5] or conveyor transport [6]. It is time to move from transport systems with discrete cargo flows to systems with combined cargo flows created by dump trucks, railway transport and belt conveyors, which is already observed in a number of quarries in Russia, Ukraine, Uzbekistan and Kazakhstan [7, 8].

It should be noted that in Poland, at one of the largest open-pit mines in the world for the extraction of brown coal, the most widely used is the converter method of transporting the mined products [9, 10]. Technology engineering is being continuously improved in the direction of increasing the productivity and energy efficiency [11, 12].

In recent years, there have also been intensive searches for more progressive solutions associated with the use of steeply inclined belt conveyors, which allow transporting crushed hard rocks and ores at an angle of 30–45° or more, i.e. increasing the angle of inclination in comparison with the used conveyor lifts (usually no more than 16°) by two or more times.

At the same time, taking into account that a very significant modernization of career vehicles has recently occurred – dump trucks began to be produced with the best traction-dynamic and ecological characteristics, this allows us to hope that the rational area of their application can be expanded. One of the ways to expand the rational field of use of mining dump trucks can be the use of inertial forces of a moving dump truck to overcome inclines. The principal differences of the process under consideration from the existing one as follows.

The objective of the article is to improve the efficiency of motor vehicles while changing structures of slopes of transport inclines in the context of open pit mineral mining.

Presentation of the main research. At present, the process of transporting the rock mass by dump trucks is carried out by creating a dump truck wheels of the tangential traction force (Fig. 1). The tangential traction force, in turn, is determined by the power, the torque developed by the engine, the transmission ratio (gearbox, final drive and wheel transmission) and the rolling radius of the wheels. But regardless of the above, the maximum value of the tangential traction force is limited in adhesion (the friction force between the tire of the wheel and the surface of motion). It is a well-known situation when the wheels of a car on a section with a low coefficient of friction (for example, an icy surface) begin to slip, unable to move the car from a standstill.

In addition, one of the drawbacks of overcoming large inclines due to the implementation of the tangential traction force of the drive wheels is that by realizing the tangential traction force on the inclines, the drive wheels move with slipping (the more the slope, the more slip). As a result, the driving wheel tires are subject to intense wear. For comparison, the wear of the front tires is not leading (slave) wheels several times less than tires of driving wheels.

It is these two factors (engine load with transmission [13] and tire wear) that now determine the rational amount of steering bias in the transport inclines of modern quarries. According to the requirements of the USSR (Uniform Safety Rules) [14], its value is 8–10 %.

Let us consider the forces causing the acceleration of a given body, and the forces of inertia resulting from ac-

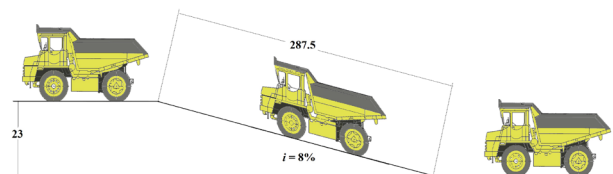


Fig. 1. The existing scheme to overcome the slope by the dump truck

celeration. They are always equal in magnitude and oppositely directed. Consequently, the forces of inertia with the existing scheme of the movement of dump trucks are harmful forces, for overcoming which additional energy of the engine is expended and fuel is consumed during movement and braking.

The analysis of the laws of physics shows that, as applied to career road transport, with proper organization of motion schemes, these inertia forces can also have a positive effect if these forces are directed at overcoming resistances to the motion of a dump truck.

The magnitude of the force of inertia depends on the mass of the body and the acceleration of its movement. Considering that mining dump trucks have a large mass (tens of tons), then with an average speed of movement of 4.2 m/s, the inertial force can reach significant values (tens, and even hundreds of kN). These forces can be directed to overcome the slopes in the transport inclines (Fig. 2).

Equations of kinematics of uniformly variable (equally accelerated or equally slow) motion in the projection on the axis OX have the generally known form

$$x = x_0 + V_{x0} \cdot t + a_x \cdot t^2/2;$$

$$V_x = V_{x0} + a_x \cdot t,$$

where x is the distance traveled by the body; x_0 is initial body position; V_{x0} is initial translational velocity at a point x_0 ; t is body movement time; a_x is acceleration of body movement.

For example, we'll conduct a simplified calculation, according to the well-known method, of the main parameters of the movement of the BelAZ 7547 dump truck, under the specified conditions: loading capacity – 45 t; own weight – 33.1 t; power plant power 368 kW; maximum torque (at 1600 rpm) 1815 Nm; gear ratios: 1 – 3.84; 2 – 2.27; 3 – 1.50; 4 – 1.055; 5 – 0.625; total gear ratio of driving bridge – 20.5; wheel radius – 1 m. We will assume that the movement is carried out on haulage roads with crushed stone coating (the coefficient of specific ground resistance is $\omega_o = 40$ N/kN).

Consider the possibility of overcoming the transport inclines, the slope of which is 30 %, by a truck. The greatest tangential traction force F_c (N), necessary to overcome the total resistance to movement for the case of movement of a loaded car in a transport inclines, can be determined from the relation

$$F_c \geq \sum W = W_o \pm W_i + W_k + W_j$$

where \sum is total resistance to movement; W_o is main resistance to movement, N; W_i is resistance from road

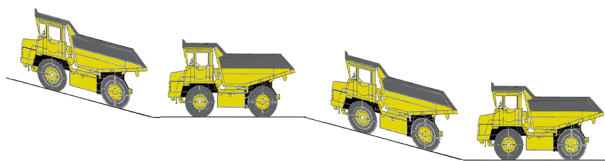


Fig. 2. Overcoming large slopes of small extent due to inertia forces

slope, N; W_k is resistance on curved paths, N; W_j is resistance of inertia forces, N

$$W_o = \omega_o \cdot P \cdot g = 40 \cdot 78.1 \cdot 9.8 = 30\ 615.2,$$

where P is weight of the loaded car, t; g is acceleration of gravity, m/s^2

$$P = P_a + P_l = 45 + 33.1 = 78.1,$$

where P_a is empty car weight, t; P_l is the mass of the cargo in the back of the car, t

$$W_i = i \cdot P \cdot g = 300 \cdot 78.1 \cdot 98 = 229\ 614,$$

where i is transport inclines slope 30 %

$$W_k = P \cdot g \cdot \omega_k = 78.1 \cdot 9.8 \cdot 225 = 17\ 221.05,$$

where $\omega_k = 30 \cdot \frac{200 - R}{200} = 22.5$ is resistivity on curved road sections, N/kN; $R = 50$ is the radius of the road curves, m.

$$W_j = 102 \cdot P \cdot g \cdot (1 + \gamma) \cdot a = 102 \cdot 78.1 \cdot 9.8 \cdot (1 + 0.03) \cdot 0.1 = 7830.3,$$

where γ is the coefficient taking into account the inertia of the rotating masses of the car ($\gamma = 0.01-0.03$); a is car acceleration or deceleration, m/s^2 ($\alpha = 0.1-0.2$).

$$F_c \geq \sum W = W_o \pm W_i + W_k + W_j = 30\ 615.2 + 229\ 614 + 17\ 221.05 + 7830.3 = 285\ 280.55.$$

If we represent the dump truck as a moving body of translation, then the equation of the dynamics of translational motion, projected on the axis OX , can be written

$$P \cdot a_x = \sum F_c$$

Since the mass of the loaded dump truck is known to us, as well as the resistance forces, we can determine the amount of deceleration of the dump truck when it is moving up

$$a_x = F_c/P = 285\ 280.55/78\ 100 = -3.65.$$

If we consider the kinematics equation of uniformly varying body motion moving progressively in the projection on the axis OX , we can obtain

$$x = x_0 + V_{x0} \cdot t - a_x \cdot t^2/2. \tag{1}$$

Let us set the initial speed of the loaded car to 6.9 m/s and according to the equation

$$V_x = V_{x0} - a_x \cdot t, \tag{2}$$

we can determine the time after which the car will stop on the slope

$$t = V_{x0}/a_x = 6.9/3.65 = 1.9.$$

Substituting the obtained value of time into equation (1), we determine the distance traveled by the car to a full stop on the slope

$$x = 0 + 6.9 \cdot 1.9 - 3.65 \cdot 1.9^2/2 = 6.6.$$

This value of 6.6 meters represents the distance that the dump truck will travel by inertia, with the engine off.

If at this site the traction force developed by the engine is used, the distance should increase.

The dependency to determine it will be

$$P \cdot a_x = F_k - F_c, \quad (3)$$

where F_k is tangential traction force developed by dump truck wheels.

$$F_k = M_k \cdot R_k,$$

where M_k is torque developed by the dump truck wheels; R_k is wheel rolling radius.

In turn, the value of M_k is determined by the rotational speed of the engine crankshaft and the transmission ratio. If we take the maximum torque of the engine at 1600 rpm $M_e = 1815$ Nm, then with different gear ratios of the gearbox, the desired tangential thrust force will be equal to:

$$\begin{aligned} 1 \text{ gear } M_k &= M_e \cdot i_1 \cdot i_o = 1815 \cdot 3.84 \cdot 20.5 = 142\,876.8; \\ F_k &= 142\,876.8 \cdot 1 = 142\,876.8 \text{ N}; \\ 2 \text{ gear } M_k &= M_e \cdot i_2 \cdot i_o = 1815 \cdot 2.27 \cdot 20.5 = 84\,461.025; \\ F_k &= 84\,461.025 \cdot 1 = 84\,461.025 \text{ N}; \\ 3 \text{ gear } M_k &= M_e \cdot i_3 \cdot i_o = 1815 \cdot 1.50 \cdot 20.5 = 55\,811.25; \\ F_k &= 55\,811.25 \cdot 1 = 55\,811.25 \text{ N}; \\ 4 \text{ gear } M_k &= M_e \cdot i_4 \cdot i_o = 1815 \cdot 1.055 \cdot 20.5 = 39\,253.9; \\ F_k &= 39\,253.9 \cdot 1 = 39\,253.9 \text{ N}; \\ 5 \text{ gear } M_k &= M_e \cdot i_5 \cdot i_o = 1815 \cdot 0.625 \cdot 20.5 = 23\,254.7; \\ F_k &= 23\,254.7 \cdot 1 = 23\,254.7. \end{aligned}$$

Consequently, depending on the transmission, the acceleration of the dump truck developed on a slope will be (3)

$$\begin{aligned} a_{x1} &= (142\,876.8 - 285\,280.55)/78\,100 = -1.82; \\ a_{x2} &= (84\,461.025 - 285\,280.55)/78\,100 = -2.57; \\ a_{x3} &= (55\,811.25 - 285\,280.55)/78\,100 = -2.94; \\ a_{x4} &= (39\,253.9 - 285\,280.55)/78\,100 = -3.15; \\ a_{x5} &= (23\,254.7 - 285\,280.55)/78\,100 = -3.36. \end{aligned}$$

Thus, we see that when driving on all gears, the acceleration takes on a negative value, and the dump truck will not be able to overcome the long slope of 30 %.

But we are talking about protracted slopes. As for the slopes of a relatively short length, a dump truck can overcome them. Above, we calculated that even with the engine completely disconnected, the dump truck run out on a 30 % slope is 6.6 meters.

If we assume that the reduction in speed when overcoming a slope should not be less than 10 km/h, then the dump truck run-down time when driving on a slope at 2 gears at a speed of 25 km/h to a speed of 10 km/h in accordance with equation (2) will be

$$t_2 = (V_{x0} - V_x)/a_x;$$

$$t_2 = (6.9 - 2.8)/2.57 = 1.6,$$

during this time the dump truck will overcome

$$\begin{aligned} x &= V_{x0} \cdot t_2 - a_x \cdot t_2^2/2 = \\ &= 6.9 \cdot 1.6 - 2.57 \cdot 1.6^2/2 = 7.75. \end{aligned}$$

Thus, taking into account the fact that the length of the slope being overcome is 7.75 meters, the height of the slope will be 2.325 meters respectively.

To overcome the next bias, the dump truck should increase the speed in a horizontal section from 10 to 25 km/h. To determine the length of the section where the dump truck reaches a speed of 25 km/h, the following relationships should be used

$$F_c \geq \sum W = W_o + W_k + W_j =$$

$$= 30\,615.2 + 17\,221.05 + 7830.3 = 55\,666.55.$$

Substituting the obtained value into dependence (3), we obtain the acceleration value with which the dump truck will move along a horizontal surface with second gear

$$a_x = (F_k - F_c)/P =$$

$$= (84\,461.025 - 55\,666.55)/78\,100 = 0.37.$$

With known acceleration, we can determine the time and length of the horizontal section where the dump truck can reach a speed of 25 km/h to overcome the next ledge

$$t = (V_{x0} - V_x)/a_x = (6.9 - 2.8)/0.37 = 11.1;$$

$$x = V_{x0} \cdot t - a_x \cdot t^2/2 =$$

$$= 2.8 \cdot 11.1 + 0.37 \cdot 11.1^2/2 = 8.29.$$

Thus, the transport incline when climbing 23 meters should have 10 benches, with slopes of 30 % and a slope length of 7.75 m, as well as horizontal sections of 8.5 m length (Fig. 3).

The overall slope of the transport incline will be 15 %, which is much higher than recommended (8–10 %).

The above calculations of the length of the horizontal and inclined sections do not take into account the value of the wheelbase of the dump truck. Taking into account the wheelbase, the length of the horizontal and inclined sections should be longer. In turn, an increase in the length of sections by the size of the wheelbase will lead to a slight increase in the magnitude of the total gradient. For example, considering that the base of the BelAZ-7547 dump truck is 4.2 meters, the length of the slope to be overcome will increase to 11.95 meters (Fig. 4), and the height of the slope will be 3.59 meters respectively.

Taking into account the base of the dump truck, the length of the horizontal section will also increase to 12.49 meters (Fig. 5).

Thus, the length of the exit incline in the presence of 10 ledges, with slopes of 30 % and a slope length of 12 m, as well as horizontal sections of 12.5 m length (Fig. 6)

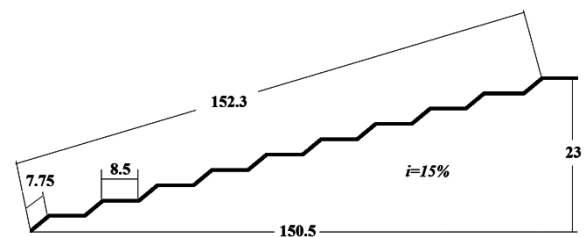


Fig. 3. Scheme of slopes for transport incline

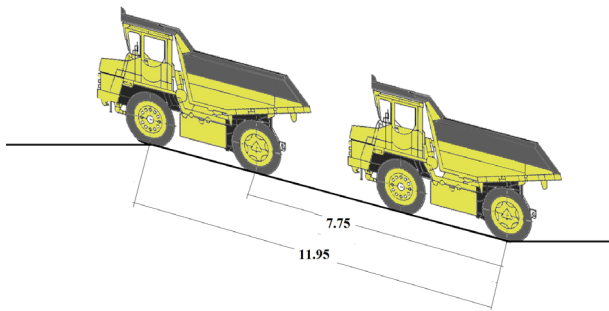


Fig. 4. Overcoming the slope of 30 %

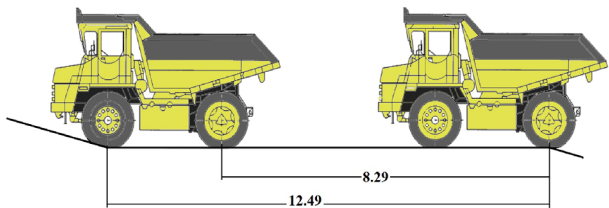


Fig. 5. Movement at the horizontal part

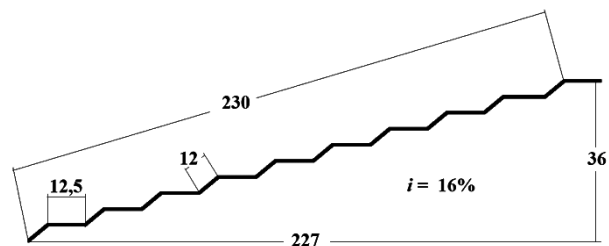


Fig. 6. The proposed scheme tilt exit incline

will be 230 m, and the exit incline height of 36 m will be 16 %.

Conclusions and recommendations for further research. Mathematical models of dynamic processes developed during the implementation of the tangential traction force of a motorized dump truck developed on elevated slopes of career paths, differing from those known by the fact that inertia forces resulting from acceleration during the motion of a dump truck are used to overcome elevated gradients in the transport inclines of quarries. Overcoming the increased slope of transport incline for open pit mines due to the use of inertial forces developed by the dump trucks during movement on horizontal sections makes it possible to halve the length of the transport incline, correspondingly, reduce the time it takes to move the dump trucks and increase productivity when transporting rock mass. In addition, the presented solution will reduce fuel consumption, tire wear and ultimately reduce the cost of mining. Moreover, the proposed scheme of the transport incline route and the mode of movement of dump trucks change the very technology of the development of mineral deposits by the open method, since increasing the slopes of the exit trenches will reduce the size of the side walling when developing deep quarries.

It is shown that these solutions are the simplest for practical use and can be made in the design of new ca-

reer routes, as well as for exploited transport inclines of deep quarries.

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Підвищення ефективності використання автосамоскидів в умовах кар'єрів на відкритих гірничих роботах

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Мета. Підвищення ефективності роботи автомобільного транспорту шляхом зміни структури ухилів виїзних траншей на відкритих гірничих розробках родовищ корисних копалин.

Методика. У роботі використано теоретичний аналіз, заснований на методах теорії використання діючих сил інерції рухомого автосамоскиду для подолання підвищених ухилів траси руху. Аналіз і узагальнення аналітичного способу вирішення рівнянь кінематики рівнозмінного (рівноприскореного або рівносповільненого) руху автосамоскидів використовувалися з метою підтвердження теоретичних результатів і прийнятих припущень.

Результати. У роботі зроблена спроба узагальнити, розвинути й запропонувати більш повні рішення задач раціональної області застосування кар'єрних автосамоскидів за рахунок використання сил інерції автосамоскиду, що рухається для подолання підвищених ухилів трас кар'єрних доріг. Наведене аналітичне рішення тягових і гальмівних завдань при подоланні автосамоскидами ухилів виїзних траншей при відкритій розробці родовищ. Показано, що ці рішення найбільш прості для практичного використання при проектуванні нових кар'єрних трас при експлуатації виїзних траншей глибоких кар'єрів.

Наукова новизна. Розроблені математичні моделі динамічних процесів, що протікають при реалізації дотичної сили тяги, що розвивається двигуном автосамоскиду на підвищених ухилах кар'єрних трас. Вони відрізняються від відомих тим, що в якості основного моделюючого елемента використовуються сили інерції, що виникають унаслідок

прискорення при русі автосамоскиду, які можна направити на подолання підвищених ухилів у виїзних траншеях кар'єрів. У результаті чисельного моделювання встановлені закономірності зміни швидкості руху автосамоскидів при змінюваності горизонтальних і похилих ділянок дороги в залежності від їх протяжності та кутів нахилу. Це дозволяє вдосконалити виробничий процес за критерієм подоланих підвищених ухилів виїзних траншей кар'єрів, майже вдвічі скоротити їх довжину, скоротити час руху самоскидів і підвищити продуктивність при транспортуванні гірської маси.

Практична значимість. Отримані в роботі результати, представлені у вигляді розрахункових формул, дозволяють обґрунтовано проводити розрахунки трас виїзних траншей при відкритій розробці родовищ корисних копалин на етапі проектування кар'єрів. Це забезпечує зниження величини рознесення бортів при розробці глибоких кар'єрів.

Ключові слова: автосамоскид, ухил, дотична сила тяги, коефіцієнт тертя (зчеплення), відкриті гірничі роботи

Повышение эффективности использования автосамосвалов в условиях карьеров на открытых горных работах

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Цель. Повышение эффективности работы автомобильного транспорта путем изменения структуры уклонов выездных траншей на открытых горных разработках месторождений полезных ископаемых.

Методика. В работе использован теоретический анализ, основанный на методах теории использования действующих сил инерции движущегося автосамосвала для преодоления повышенных уклонов трассы движения. Анализ и обобщение аналитического способа решения уравнений кинематики равнопеременного (равноускоренного или равнозамедленного) движения автосамосвалов использовались с целью подтверждения теоретических результатов и принятых допущений.

Результаты. В работе сделана попытка обобщить, развить и предложить более полные решения задач рациональной области применения карьерных автосамосвалов за счет использования сил инерции движущегося автосамосвала для преодо-

ления повышенных уклонов трасс карьерных дорог. Приведено аналитическое решение тяговых и тормозных задач при преодолении автосамосвалами уклонов выездных траншей при открытой разработке месторождений. Показано, что эти решения наиболее простые для практического использования при проектировании новых карьерных трасс при эксплуатации выездных траншей глубоких карьеров.

Научная новизна. Разработаны математические модели динамических процессов, протекающих при реализации касательной силы тяги, развиваемой двигателем автосамосвала на повышенных уклонах карьерных трасс. Они отличающихся от известных тем, что в качестве основного моделирующего элемента используются силы инерции, возникающие вследствие ускорения при движении автосамосвала, которые можно направить на преодоление повышенных уклонов в выездных траншеях карьеров. В результате численного моделирования установлены закономерности изменения скорости движения автосамосвалов при чередовании

горизонтальных и наклонных участков дороги в зависимости от их протяженности и углов уклона. Это позволяет усовершенствовать производственный процесс по критерию преодолеваемых повышенных уклонов выездных траншей карьеров, почти вдвое сократить их длину, сократить время движения самосвалов и повысить производительность при транспортировке горной массы.

Практическая значимость. Полученные в работе результаты, представленные в виде расчетных формул, позволяют обоснованно производить расчеты трасс выездных траншей при открытой разработке месторождений полезных ископаемых на этапе проектирования карьеров. Это обеспечивает снижение величины разности бортов при разработке глубоких карьеров.

Ключевые слова: автосамосвал, уклон, касательная сила тяги, коэффициент трения (сцепления), открытые горные работы

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