INFLUENCE OF THE ARRANGEMENT AND PERFORMANCE OF SHOVELS ON THE OPTIMUM POSITION FOR RUN-OF-MINE STOCK LOCATION

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ABSTRACT. The purpose of this paper is to develop a methodology to determine the coordinates of an optimum point for run-of-mine stock and influence of spacious arrangement of excavation faces on an optimum point of run-of-mine stock location. This article represents an overview of studies, where algorithms of the Fermat-Torricelli point are used in order to minimize the logistic processes. The methods of mathematical optimization and analytical geometry were applied in this work. It is proved that when the performance of one of the shovels is 1.7 times greater than the performance of the others, the Fermat-Torricelli point shifts to this shovel. The undertaken studies are aimed first at optimization of road and rail transport in the open pit mines. Considering an optimization of haulage for a group of three shovels, it is obvious that moving the rock mass from two shovels to the working area of the third one, which has the highest capacity we thereby determine an optimum position of the reloading point for the shovel. Since the depth of the open pit grows, the railway transport loses its efficiency mainly not because of the lesser gradient in comparison to the road transport, but because of the need to freeze a section of the pit wall in order to locate the reloading points for shovels. By eliminating the afore-mentioned shortcoming, it is possible to improve significantly the efficiency of haulage in the open pit mine. The article considers a new method of arranging and operating a reloading point for shovels.

Keywords: reloading station, Fermat-Torricelli point, minimum haulage

ВЛИЯНИЕТО НА РАЗПОЛОЖЕНИЕТО И ПРОИЗВОДИТЕЛНОСТТА НА ЕДНОКОФОВИТЕ БАГЕРИ ВЪРХУ ОПТИМАЛНОТО МЕСТОПОЛОЖЕНИЕ НА НЕОБРАБОТЕНАТА МИННА ПРОДУКЦИЯ ОТ ДНЕВНИЯ ДОБИВ

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РЕЗЮМЕ. Целта на настоящата разработка е да се разработи методология за определяне на координатите на оптималното местоположение на необработената минна продукция от дневния добив и влиянието на пространственото разположение на добивните забои върху оптималното местоположение на необработената минна продукция. В статията представен е прегледа на изследванията, в които за минимизиране на логистичните процеси се прилагат алгоритми с използване на точката на Торичели-Ферма. В работата се използват методите за математическа оптимизация и аналитична геометрия. Доказано е, че когато производителността на единия от еднокофовите багери е 1,7 пъти по-голяма от производителността на другите, точката на Ферма-Торичели се пренасочва към този багер. Извършените изследвания са насочени преди всичко към оптимизиране на автомобилния и железопътен транспорт в открити рудници. Като се има предвид оптимизирането на транспорта за група от три еднокофови багера, е очевидно, че чрез преместване на скалната маса от два багера в работния обхват на третия, който е с по-висока производителност, определяме оптималното положение на точката на претоварване на багера. С увеличаването на дълбочината на рудника, железопътният транспорт губи своята ефективност не поради по-малкия наклон в сравнение с автомобилния транспорт, а поради нуждата от замразяване на участък от рудничния борт, за да бъдат локализирани точки на претоварване на багерите. Преодолявайки гореспоменатите недостатъци, е възможно значително да се подобри ефективността на рудничния транспорт. В доклада се разглежда нов начин за разполагане и експлоатация на претоварните точки на багерите.

Ключови думи: точка за претоварване, точка на Торичели-Ферма, минимизиране на транспорта

Introduction

Background of the problem and its relation to practical issues

To minimize the transport work during open pit mine design, determination of the rational point of mining mass dumping is important. This task arises during the justification of the rational position of the reloading point of combined mine transport. The analysis of the design decisions on the combined transport usage shows that the position of reloading points often unfavorably affects the dynamics of mining operations (Яковлев, 1989; Вилкул и др., 2008; Vilkul et al., 2016; Белозеров, 2012; *Арсентьев*, 1986; Слободянюк и др., 2006). Reloading points that suspend mining operations in the lower part of the open pit mine side occur mainly in open pit mines. Such solutions reduce the economic efficiency of mining operations. In the theory of mining, insufficient attention has been devoted to problems of optimization of parameters, such as volume and location, of the reloading point (for instance temporary dump) that provides a minimization of the transportation work for haul trucks.

Analysis of recent studies and publications

In the mining and many other industries, the problem of determining an optimum point for run-of-mine (RoM) stock (an optimum location of the reloading point) that minimizes the cumulative haulage volume (S is Fermat-Torricelli point) is topical. Throughout 350 years, several methods have been proposed for determining the optimum point, but they have some drawbacks and are not universal (*Протасов*, 1989; *Успенский*, 1958). A detailed analysis of the geometric methods (proposed in the XVII-XIX centuries) and an analysis of influence of the shape and dimensions of the triangle on the change in the position of the point S are made in (Slobodyanyuk et al., 2017), and formulas for the coordinates of the point S for the quadrangle are given. Similar formulas for the triangle cannot be applied because of the uncertainty of some intermediate operations (the uncertainty of the sign when the square root is found; the formulas vary for points "on the left" or "on the right", "on the top" or "on the bottom").

In (Slobodyanyuk et al., 2017; Максимов и.Слободянюк, 2017), the authors proposed a universal gradient method to find the point S for any quantity of points *n* with the same or different performance. Applying the simple formulas, we first find the coordinates of the gravity center (a starting point) and the volume of road haulage for the selected point and eight adjacent points (in different directions, at a distance of ±Δx; ±Δy); from nine points we choose the point with the lowest haulage volume and so on until the optimum point S is finally found.

Main Exposition

Formulation of the problem

The purpose of this article is to investigate the specific features of the influence of excavating face capacity on the position of the optimum point for RoM stock at three excavating faces, and to justify the results obtained in the context of further improvement of combined road and rail transport.

Presentation of the main study material

The methods proposed and developed earlier do not allow us to analyze the behavior of change in the cumulative haulage volume with change in the position (coordinates) of the RoM stock point; the dependence of the coordinates of the optimum point S on the parameters of the triangle is not determined. Similar methods have led to a system of irrational equations that do not give an unambiguous answer (the reasons were given above). In this paper we analyze the position of the optimum point for some symmetrical figures for which one of the coordinates is known (e.g., $y_S=0$). Let us consider an isosceles triangle with a center of the coordinate system located in the middle of the triangle base (Fig. 1).

If the face capacities are the same (Q), the cumulative transport operations are:

$$F(x) = Q\left[2\sqrt{\frac{a^2}{4}+x^2}+(b-x)\right] \Rightarrow \min \qquad (1)$$

Let us find the derivative, equate to zero and obtain the equation:

$$\frac{2x}{\sqrt{\frac{a^2}{4}+x^2}} - 1 = 0 \qquad (2)$$

We finally find:

$$x = \frac{a\sqrt{3}}{6} \qquad (3)$$

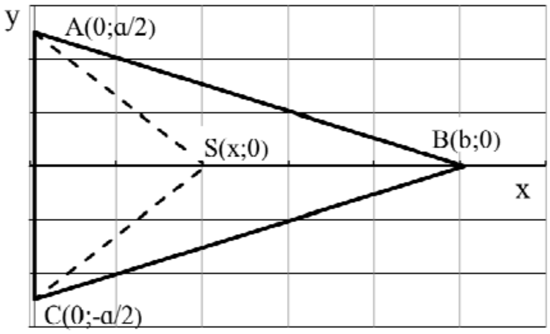

Fig.1. Diagram for finding the optimum point for RoM stock for an isosceles (symmetrical) triangle (AB = BC)

The resulted value corresponds to the geometric solution (Slobodyanyuk et al., 2017) and is equal to half the radius of the circle circumscribed about the Napoleon’s equilateral triangle, constructed "on the left" on ***AC=a***. The conclusion that the position of the optimum point depends only on the parameter ***a*** and does not depend on the distance ***b***, where the point ***B*** is situated is confirmed. While the point ***B*** is moving off along the ***OX*** axis, the position of the optimum point does not change.

Let us consider a similar problem provided that the performance of point ***B*** is greater (or less) than the performance of points ***A*** and ***C*** and is equal to ***K·Q***, where ***K*** is some coefficient. Then, equation (2) takes the form as follows:

$$\frac{2x}{\sqrt{\frac{a^2}{4}+x^2}} - K = 0 \qquad (4)$$

Finally, we find:

$$x = \frac{a}{2} \times \frac{K}{\sqrt{4-K^2}} \qquad (5)$$

At ***K = 1***, the performance of points ***A; B; C*** is the same, we get the value (3). At ***K=2*** (the performance of point ***B*** is twice the performance of points ***A*** and ***C***), we obtain ***x→∞***. In view of the physical and geometric meanings of the problem, the optimum point for RoM stock will be point ***B***. This conclusion coincides with the other researchers’ conclusions obtained by modeling.

We set the positions of points ***A, B, C*** on the solid surface (model) and make holes in these points. Using the laces run through the holes, we hang the weights and tie the laces. The position of the knot corresponds to the position of the optimum point for RoM stock (*Протасов*, 1989; *Успенский*, 1958). If the weight corresponding to the point ***B*** is doubled, then the knot "falls through" to the point ***B*** (i.e., the point ***B*** is an optimum point for RoM stock). In (Максимов и.Слободянюк, 2017) this conclusion is proved by geometric methods. It is easy to verify this conclusion if two adjacent vertices of the quadrangle infinitely approximate one another, then the point of intersection of the diagonals approaches this double point (the point of intersection of the diagonals for the quadrangle is the Fermat-Torricelli point). A similar conclusion follows from (5), being a more rigorous proof.

We substitute in formula (5) the value ***x=b*** and find the coefficient ***K*** at which the point ***B*** will be optimum:

$$b = \frac{a}{2} \times \frac{K}{\sqrt{4-K^2}}; \quad \rightarrow \quad K = \frac{2b}{\sqrt{b^2 + \frac{a^2}{4}}} \qquad (6)$$

For an equilateral triangle ABC $b = \frac{a\sqrt{3}}{2}$ and we have $K = \sqrt{3} \approx 1.73$.

The point ***B*** will be optimum at its performance (by 73% higher than the performance of points ***A*** and ***C***). When the point ***B*** is moving off, the value of the coefficient ***K*** increases, at ***b = 2a K = 1.95***. Fig. 2 shows a function graph (6), which reflects the nature of increasing the coefficient ***K*** when the point ***B*** moves off.

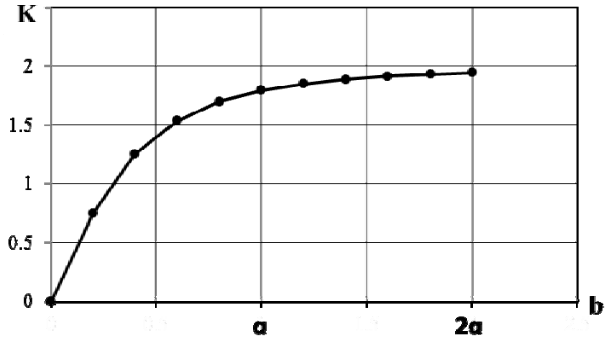

Fig.2 The graph of change in the parameter K when the point B moves off

Fig. 3 shows a graph of the function (1), i.e. the cumulative haulage volume. From the graph it is evident that the lowest tonnage will be available when the reloading point is located at the optimum point (Ferma-Torricelli) at $x = \frac{a\sqrt{3}}{6}$. With increasing ***x***, the cumulative tonnage increases, and with ***x>a***, the increase is proportional to the distance ***x***.

Function (1) has an oblique asymptote *y=Q(x+b)*, that indicates a proportional increase in tonnage (*x>a*). The efficiency of choosing the optimum point for RoM stock will be considered using an equilateral triangle. When hauling the rock mass to one of the triangle vertices, the cumulative haulage volume is ***2aQ***. When placing the point for RoM stock in the middle of either side (the point ***O***, Fig. 1) the cumulative tonnage is $a \times Q\left(1 + \frac{\sqrt{3}}{2}\right) \approx 1.87a \times Q$ (decreases by 6.7%), and when choosing the optimum Fermat-Torricelli point the cumulative tonnage is $a \times Q\sqrt{3} \approx 1.73a \times Q$ (decreases by another 7.2%).

A similar study of changing the cumulative haulage volume was made for the case when the performance of the point ***B*** was twice as large as the performance of points ***A*** and ***C***. Formula (1) looks like this:

$$F(x) = Q\left[2\sqrt{\frac{a^2}{4} + x^2} + 2(b-x)\right] \qquad (7)$$

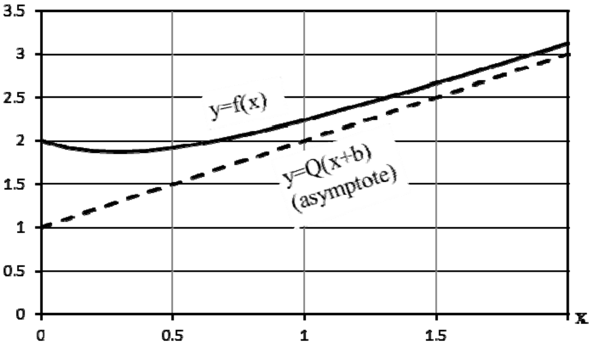

Fig.3. Change in the cumulative haulage volume when moving the point for RoM stock along the OX axis

However, the optimum point for RoM stock (Fermat-Torricelli) is point ***B***. Analysis of the graph (Fig. 4) shows that when shifting the point for RoM stock from the point O to the point ***B***, the cumulative haulage volume is reduced by 30%.

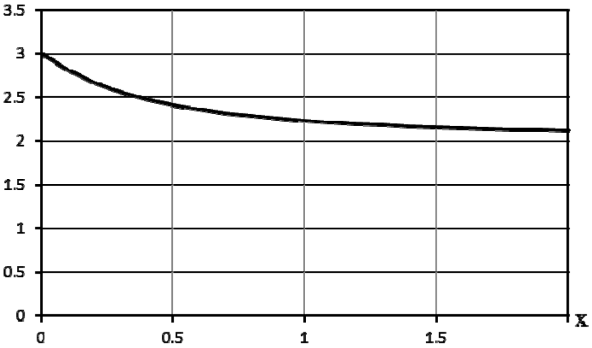

Fig.4. Change in the haulage volume for the case when the performance of the point B is twice as large as points A and C

Comparison of graphs (Fig. 3, 4) shows that with increasing the performance of the point ***B***, the behavior of the cumulative haulage changes drastically.

The undertaken studies are primarily aimed at optimization of road and rail transport in the open pit mines. Considering an optimization of haulage for a group of three shovels, it is obvious that moving the rock mass from two shovels to the working area of the third one, which has the highest capacity, we thereby determine an optimum position of the reloading point and open pit face for the shovel with a "zero" truck haulage (i.e. for the shovel operating for the second link of combined transport - rail transport).

Since the depth of the open pit grows, the rail transport loses its efficiency mainly not because of the lesser gradient (30-40‰ vs. 80‰) in comparison to the road transport, but because of the need to freeze a section of the pit wall in order to locate the reloading points for shovels. By eliminating the afore-mentioned shortcoming, it is possible to improve significantly the efficiency of road and rail haulage in the open pit mine. The article (Slobodyanyuk, Turchin; 2017) proposes a new method of arranging and operating a reloading point for shovels.

The drawbacks of reloading points equipped with the rope shovels are that during operation of the reloading point, the trucks and dump cars intersect, which leads to a decrease in the tonnage capacity of trucks, and unloading the trucks at a level higher than the shovel is located makes it impossible to combine the handling operations in time and space. This causes a decrease in the shovel performance and an increase in the distance haulage of rock mass by trucks. In order to locate the reloading point, it is necessary to deactivate a section of the pit wall that resulted in a decrease in the rock mass output. The developed technology reduces the negative impact of reloading points on the dynamics of mining operations, increases the tonnage capacity of trucks due to eliminating the additional lift of rock mass by trucks and avoiding the intersection of roads and railways (Fig.5).

The mining operations using the developed technology are made as follows (Figure 5). A backhoe hydraulic shovel (1) excavates a receiving trench (2). This trench (2) is conditionally divided by width into two sections: the unloading wall (3) and the loading wall (4). The receiving trench (2) is filled with rock mass on the unloading wall (3) by trucks (5). In the general case, in order to prevent from intersecting the haul roads, the receiving trench wall (2) located closer to the lower pit benches is the unloading wall (3). The receiving trench wall located closer to the higher pit benches is the loading wall (4). The rail track is located (7) along the loading wall (4) of the receiving trench (2).

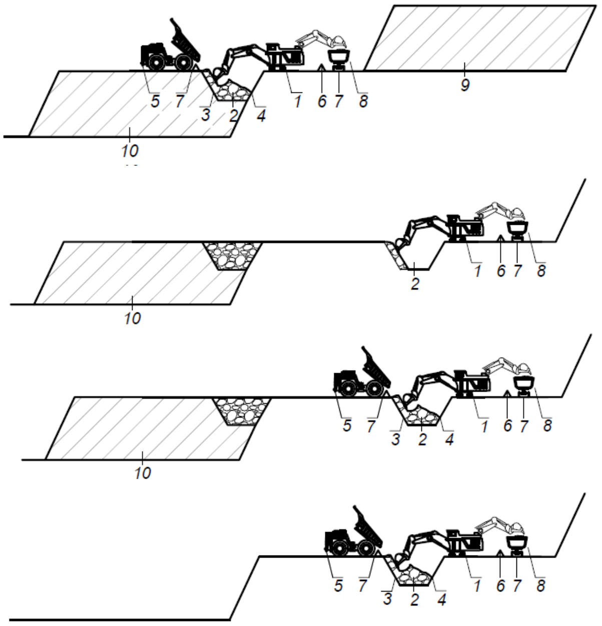

Fig.5. Diagram of mining operations when shifting a reloading point

The rock mass from the receiving trench (2) is reloaded by a hydraulic shovel (1), located on the loading wall (4) of the receiving trench (2) onto dump cars (8) located at the level of the hydraulic shovel.

The reloading point in the given place operates until the higher benches (8) are mined out. After this, a backhoe hydraulic shovel (1) excavates a new receiving trench (2) on the extended site. After commissioning the relocated reloading point, the lower benches (9) are mined out. In order to increase the capacity of the reloading point, two or more backhoe hydraulic shovels are placed on the loading trench wall at a safe distance from each other. The use of the proposed reloading point design provides an increase in the capacity of mining equipment and reduces the negative impact of open pit transport on the dynamics of mining operations. The reloading point of the proposed design is easily relocated as the mining operations progresses and does not freeze the pit wall.

Conclusions and trends for further studies

The use of a simplified model (an isosceles triangle) made it possible to conduct an analytical study, to find the coordinates of the optimum point for RoM stock at different performance of three points, to determine the behavior of change in the haulage volume when the point of stock was moved. In the future, similar studies are planned to be conducted for more points.

Minimum operation of three shovels, one of which has a higher performance (1.5-1.7 times higher) is ensured if the point for RoM stock tends to the location of the shovel with maximum performance. This rule determines the general approach to separation of open pit space into the operating zones for combined transport.

Minimum operation of the open pit transport, being the first link of road and rail transport, will be provided, if the truck haulage distance of maximum rock tonnage to the reloading point will be minimum. This imposes a number of requirements on the optimum mining technology, such as the use of more powerful shovels on the border of adjacent links of combined transport and the possibility of operating the second link of combined transport without freezing the working pit wall. The second requirement is fulfilled when using the developed design of the reloading point for shovels.

In further studies, the developed mathematical apparatus will be used to establish the regularities for the optimum location of reloading points and temporary truck dumps and to provide the conditions for circular truck routing.

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