Rationale of effective technological scheme for granite quarry mining

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Abstract. The paper examines the technological scheme for granite mining with the use of rock chutes in the conditions of the Rybalsky Quarry. The research purpose is to substantiate effective technological schemes for mining the upper granite quarry horizons to reduce mining costs and improve the final product quality. Research is conducted using: the method of scientific analysis, theoretical research and practice of project and production organizations; mining-geometric calculations; variant method for comparing and selecting technological schemes for mineral mining. As a result, the dependence of the transportation cost of 1 ton of mineral on the transportation distance has been determined, due to which it became possible to assess the effectiveness of using rock chutes in the conditions of the Rybalsky Quarry. The dependence of the rock chute inclination angle on the friction coefficient when rolling down the mined mass has been revealed, which substantiates the rational inclination angle of the rock chute for quarry conditions. Practical value of the research results consists in reducing the cost of transporting minerals from the upper quarry horizons by applying a technological scheme with the mined mass movement using rock chutes.

1 Introduction

Due to the growing capacity of the construction industry and increasing volumes of civil construction in major cities of Ukraine, the demand for construction minerals has increased significantly [1 – 3]. One of the main building materials is crushed stone products mined from granite quarries. In this regard, quite a large number of granite quarries have been reconstructed and equipped with modern mining equipment. This has made it possible to achieve high labor productivity and efficiency. One such enterprise is the Rybalsky Granite Quarry (Dnipropetrovsk Oblast), which uses modern crushing-screening complexes located directly in the quarry [4 – 6].

According to the degree of weathering, the minerals mined in the Rybalsky Quarry are divided into 2 varieties: weathering-disturbed and unaltered granite migmatites. Two varieties are identical in their petrographic characteristics and differ only in their physical state [7 – 10].

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Unaltered and weathering-disturbed migmatites by physical-mechanical parameters meet the requirements for the production of crushed stone products, however, they have different densities and fracturing, which affects the final quality of the finished products.

The field mining project envisages an increase in productivity and deepening of the quarry with spacing of the quarry walls. The wall spacing technology includes mining of minerals from the upper horizons, which are represented by weathering-disturbed migmatites. Since the crushing-screening complex is located on the lower horizons of the quarry, there is a need to transport mineral from the upper to the lower horizons for processing and averaging the quality of crushed stone products. In this regard, an urgent scientific-practical task is to substantiate effective technological schemes for field mining while transporting minerals from the upper horizons to the crushing-screening complex located at the bottom of the quarry.

2 Analysis of technological schemes for transporting mined mass to lower horizons

According to the geological conditions of the field and the physical-mechanical properties of the mineral, a transportation system of mining with parallel movement of the work front and external dumping has been adopted in the Rybalsky Quarry. Migmatites are loosened by the drilling and blasting method using blasthole charges. Mined mass is loaded by a Hyundai 520 LC-9S excavator with a bucket capacity of 3.2 m^3. According to the available equipment and the mineral thickness, the mining of mineral is conducted with six benches up to 15 m high.

To load minerals into automobile transport from an intermediate storage facility, KOMATSU WA500-6H front loaders with a bucket capacity of 4 – 5 m^3 are used.

Mineral is transported to the crushing-screening complex by dump trucks with a carrying capacity of up to 30 tons (BilAZ-7540). The average mineral transportation distance to the concentration horizon is 2 km. When mining the upper horizons of the Rybalsky Quarry, there is a need to transport mined mass to the concentration horizon in the crushing-screening complex with loaded dump trucks moving downwards [11]. This, in turn, leads to rapid wear of the braking system and dump truck engines. Transportation of minerals from upper to lower horizons is not typical for quarries, but when mining highland fields, special transport is often used precisely for the descent of mined mass.

Many fields of building materials are located in highland areas, with highly rugged terrain, for example, in areas of the Caucasus, Central Asia, etc. Often the problem of mining such fields consists of choosing an effective mode of transport, one of which is gravity transport [12].

With gravity transport, the mined mass is moved under the influence of its own weight. The advantages of this type of transport compared to automobile and rail transport are: no need to build roads to transport mined mass from the upper horizons; reduced transportation time; reduced rolling stock fleet, cost efficiency; compared to inclined cable hoists – no haulage ropes, rail tracks, vehicles and auxiliary devices requiring additional capital expenditure, energy, lubricants, etc. The disadvantages are the special costs for driving capital workings for the descent of the mined mass, as well as limited cases of application.

Gravity transport means include rock chutes and muck raises. Rock chute is an inclined surface working, driven on a steep mountain slope with an angle of 45 – 50º or more, which is designed to transport mined mass from the upper horizons of a quarry using its own weight. The rock chutes have different shapes in plan and section, can have different angles of inclination to the horizon, they are built with and without a cover, with a hopper and unloading devices in the lower part and without an unloading hopper.

In practice, hopper rock chutes are used in mining the highland Sterlitamak Limestone Quarry. The limestone deposit is mined from the top downwards, with 15 m benches. In the quarry, two rock chutes have been built to transport the mined mass to the beneficiation plant. The upper part of the rock chutes is mined using the surface mining method, the lower part – by underground mining. In order to transport people, equipment and materials to the quarry, some quarry horizons were uncovered with semi-trenches providing access to the industrial site of the enterprise. Limestone from the quarry face to the rock chute is transported by dump trucks with a carrying capacity of 10 tons. The rock mass is loaded from the rock chute through a hopper-loader equipped with a chain feeder.

The main disadvantage of the hopper rock chute is the reduced efficiency of its use in the winter, as a result of freezing of the mined mass in the lower part. The productivity of the rock chute decreases, so in summer it was 180 – 200 tons per shift, and in winter 80-90 tons. Therefore, the mined mass in winter was transported only by dump trucks from the lower horizons. It is expedient to use hopper rock chutes in southern areas with a short and mild winter, or in quarries with a seasonal operation mode.

The problem of mined mass freezing in the hopper rock chutes has been partially solved in the Penmeanmawr Quarry in North Wales and Trevor Quarry in the USA. The product of quarries is crushed stone, the production of which has several stages of crushing, so it was proposed to perform the first stage of crushing immediately before the descent of the mined mass down the rock chute. This helped to reduce the percentage of freezing of mined mass pieces and their scattering [13].

Open rock chutes without an unloading hopper have a simpler design, the experience of design and construction of which is almost not covered in literary sources. Such a rock chute (Fig. 1) consists of an upper unloading platform, the chute itself (its inclined part) and a lower receiving platform, where the mined mass is loaded by an excavator into vehicles.

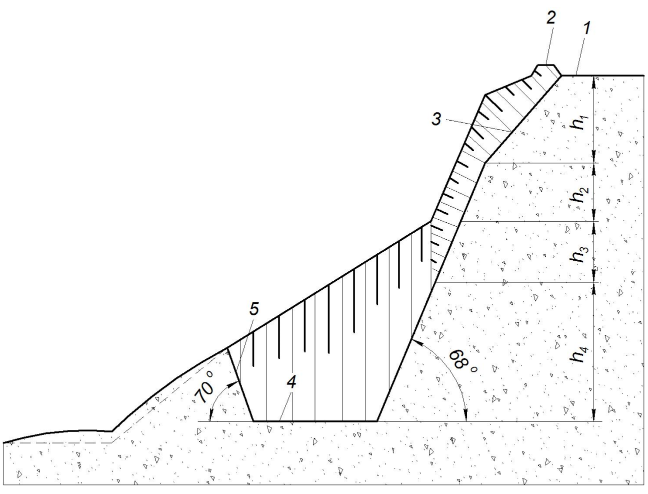

Fig. 1. Profile of a hopperless rock chute: 1 – upper unloading platform; 2 – protecting board; 3 – rock chute inclined part; 4 – lower receiving platform; 5 – protecting pillar.

The advantages of hopperless rock chutes are lower mining and capital expenditures, greater ease of construction and operation, and no plugs in unloading devices. The disadvantages are the need to reload the mined mass at the lower receiving platform of the rock chute. Hopperless rock chutes can be used in highland quarries of low productivity. Their exploitation and the general organization of work in a quarry can be significantly improved by pre-crushing the mined mass before its descent down the rock chute.

Hopperless type rock chutes are used to uncover the upper horizons in the quarry of the Ayrum crushed stone enterprise in Armenia. The raw material base of the quarry is a deposit of basalts and diorites, belonging to the highland type. The excess of the useful thickness roof above the receiving hopper level in the crushing-screening shop is about 100 m. The field is mined from top downwards with 15 m benches. Some quarry horizons were uncovered with semi-trenches adjacent to the main autoroad running from the industrial site to the quarry. In the conditions of the field, it was decided to conduct uncovering using rock chutes. On the lower receiving platform, the mined mass was loaded with an excavator onto dump trucks. The number of chutes was doubled to ensure continuous and safe operation in the quarry. To extend the service life of the rock chute lower part, it was braced by lining it with wide track rails.

The upper unloading platforms of the rock chutes were located on the working wall of the quarry. Analyzing the experience of transport systems for mined mass descent, it is proposed to explore the possibility of using hopperless rock chutes in the conditions of the Rybalsky Quarry.

3 Substantiation of an effective transportation technological scheme

The main indicator of the efficiency of the transportation technological scheme is the cost of transporting 1 ton of mineral [14].

Mineral transportation cost is calculated by the formula:

$$C_t = \frac{C_l \cdot L_t}{V_b \cdot \rho} + \frac{C_e \cdot L_t}{V_b \cdot \rho}, \text{UAH/ton}, \tag{1}$$

where C_l is the cost of loaded vehicle movement per 1 km, UAH; C_e is the cost of empty vehicle movement per 1 km, UAH; V_b is the dump truck body volume, m^3; ρ is the ore sand density, ton/m^3; L_t is the transportation length, km.

$$C_l = \frac{Q_{f.l}}{100} \cdot C_f, \text{UAH}; \tag{2}$$

$$C_e = \frac{Q_{f.e}}{100} \cdot C_f, \text{UAH}, \tag{3}$$

where C_f is the cost of 1 litr of fuel, UAH; $Q_{f.l}$ is the fuel consumption per 100 km when loaded, litr; $Q_{f.e}$ is the fuel consumption per 100 km when empty, litr.

When applying the technological scheme with rock chutes, it is necessary to take into account the fact that according to the proposed scheme, the mineral to the rock chute is transportated using BilAZ-7540 dump trucks, and from the rock chute receiving platform to the crushing-screening complex – using loaders for a distance of 0.35 km.

Given the above, the cost of transporting the mineral to different distances has been calculated, which resulted in a dependency graph of the cost of transporting 1 ton/km of granite on the transportation distance $C_t = f(L_t)$ (Fig. 2).

Analyzing the data given on the graph (Fig. 2), the transportation cost when using rock chutes is higher than when using dump trucks up to a distance of 1.1 km, but if the distance is longer, then using rock chutes becomes more profitable. This is due to the fact that when the distance of transporting the mineral increases, only the overall dimensions of the rock chutes necessarily increase, while the transportation cost does not change.

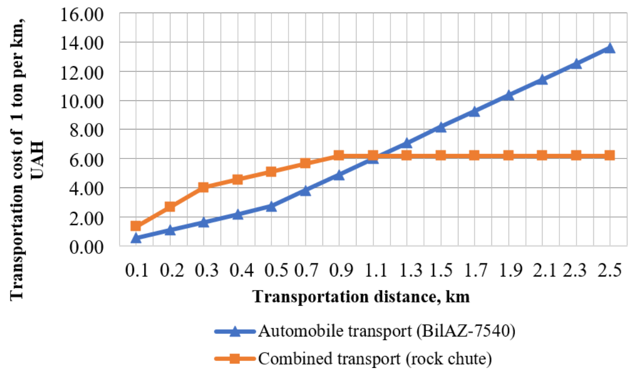

Fig. 2. Dependence of the transportation cost of 1 ton of mineral on the transportation distance.

Given that when mining the upper horizons of the Rybalsky Quarry, the average distance for transporting minerals is 2 km, the combined transport with rock chutes is more effective.

The use of combined transport can reduce the cost of transporting minerals from the upper horizons by 45.8% compared to automobile transport. This could save money:

$$\Pi = (C_{t.au.} - C_{t.r.ch}) \cdot A_{pl.\min} \cdot \rho = (11.43 - 6.19) \cdot 60000 \cdot 2.53 = 795.0 \text{ thous UAH,} \quad (4)$$

where $A_{pl.\min}$ is the planned annual volume of mineral mining, thousand m^3/year.

4 Determining the rational rock chute parameters

Creation of rock chutes in the conditions of the Rybalsky Quarry is an effective technical solution when mining the upper horizons of the quarry. In this regard, it is necessary to determine the effective location of the rock chute in the quarry and its parameters to ensure the annual mining productivity [15].

The upper horizons of the quarry are mined in the eastern direction. Therefore, it is proposed to place the rock chute in the south-eastern part of the quarry on the +40 horizon, and the lower platform – on the -10 horizon, since the crushing-screening complex is located on this horizon. Such placement of the rock chute can ensure its transportation accessibility from all upper horizons and provide an average transportation distance of 0.4 km. The total height of the rock chute is 50 m.

It is proposed to build the rock chute open without a receiving hopper and a feeder on the lower platform, thereby ensuring easy construction and reducing capital investment.

Since the upper horizons are not mined permanently, it is proposed to form a mined mass storage facility on the lower platform of the rock chute. This may simplify the organization of work and provide the opportunity to average the quality of crushed stone raw materials.

As a rule, it is recommended to use at least two rock chutes when mining highland fields. This is due to safety reasons, since the loading equipment should not be located on the lower platform of the rock chute when unloading the mined mass. The use of two adjacent rock chutes ensures continuous operation of the equipment, that is, when one is unloaded, the mined mass is removed from the platform of the second, and then vice versa. However, provided that the work is non-permanent and a temporary storage facility is arranged on the lower platform, a single rock chute is enough [16].

Capital mining operations during the construction of a rock chute directly depend on its parameters, so it is necessary to determine its effective and safe parameters.

4.1 Determining the rational rock chute inclination angle

One of the most important rock chute parameters is its inclination angle. The mined mass movement velocity and the rock chute length depend on it. The inclination angle should ensure the mined mass gravitational movement without its congestion on the inclined rock chute surface. However, the inclination angle should also dampen the very high velocity of the mined mass movement to reduce the scattering of its pieces [17].

To calculate the inclination angle of the rock chute, the following formula is used:

$$\beta = arctg \frac{2g \cdot H_{r.ch.} \cdot f_{fr}}{2g \cdot H_{r.ch.} + v_i \cdot v_f}, \text{ deg,} \tag{5}$$

where g is gravitational acceleration, g = 9.8 m/s^2; $H_{r.ch.}$ is a rock chute height, m; f_{fr} is the friction coefficient between the mined mass and the rock chute surface; v_i is an initial mined mass movement velocity, m/s; v_f is a final mined mass movement velocity, m/s.

In order to determine the rock chute inclination angle, it is necessary to determine at what final velocity of the mined mass movement the minimum scattering of pieces occurs. However, it is impossible to determine the initial and final velocity without an experiment. Therefore, it is proposed not to take into account the initial and final mined mass velocity, but to reduce the resulting angle by 1º. Thus, the formula has the form [18]:

$$\beta = arctg\, f_{fr} + (2^\circ - 3^\circ), \text{ deg.} \tag{6}$$

As can be seen from equation 6, the rock chute inclination angle depends on the friction coefficient. Therefore, the angle is calculated at different values and the dependence is plotted $\beta = f(f_{fr})$ (Fig. 3).

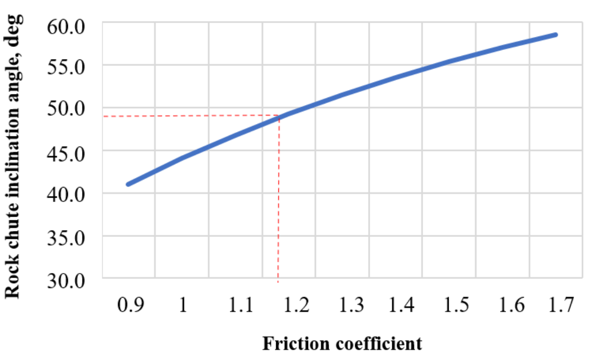

Fig. 3. Dependence of the rock chute inclination angle on the friction coefficient.

The data shown on the graph (Fig. 3) indicate that the rock chute inclination angle is directly proportional to the friction coefficient, that is, at its high values, it is necessary to increase the rock chute inclination angle. Given that the rock chute is constructed in rocks represented by granites, the friction coefficient at movement of mined mass pieces is 1.2 ÷ 1.3. Hence, the rock chute inclination angle is: β = 50º.

4.2 Determining the retaining wall height

The rock chute parameters are shown in Fig. 4.

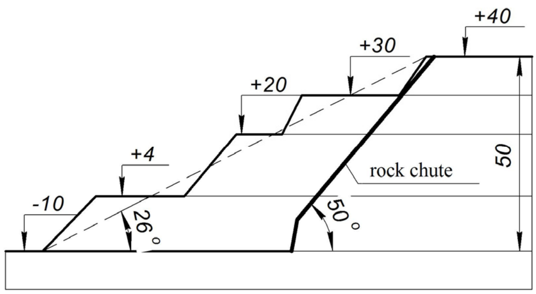

Fig. 4. Profile of a quarry wall with a rock chute.

As can be seen, when placing the rock chute on the south-eastern wall of the quarry, it is necessary to reduce the non-working sites between the benches to ensure access of the loader to the rock chute lower platform. Also, to increase the mined mass volume that can be placed on the lower platform, the slope of the lower part of the rock chute with a height of h_{sl} = 10 m is made at an angle of 80º.

To ensure the operational safety on the lower horizons of the quarry, it is advisable to create a protecting wall in the form of an embankment. Such an embankment can be constructed using hard rocks. The preliminary dimensions of the protecting wall on the lower platform can be determined using the formulas of Prof. M.M. Roynishvili [19], derived for the calculation of landslide protection structures. It should be taken into account that the formulas were derived as a result of numerous observations of the movement of individual stones from a great height down steep slopes, and not during their mass dropping, as it happens in the rock chutes. Therefore, the movement of a single stone is slightly different from the case of a mined mass movement down the rock chutes.

The required horizontal distance of the protecting embankment from the rock chute base in order to avoid stones flying over it at an inclination angle of the rock chute β = 50º can be determined by the formula:

$$l_{k.\max} = K_{range}\ H_{sl} + l_{k.z},\ \text{m}, \tag{7}$$

where K_{range} is the fall range factor, (at $H_{sl} > 45$ m $K_{range} = 0.25$), m; $l_{k.z.}$ is the technical reserve value, depending on the maximum size of a mined mass piece, m, with the piece size $d_{\max} = 1$ m^3, $l_{k.z} \geq 1$ m.

The distance of the protecting embankment placement from the rock chute base is $l_{k.\max}$ = 13.5 m. The protecting board height is chosen depending on the maximum size of a mined mass piece, for example, if a piece size is 1 m^3, a height should be 7 – 10 m.

4.3 Determining the volume of the trough and the receiving platform of the rock chute

The rock chute is a steeply inclined trench 10 – 20 m wide. A trough is formed on the slope of the rock chute to reduce the scattering of rock pieces. Therefore, when using it in granite quarries, it is also proposed to form a trough.

The cross-sectional area of the trough is:

$$S_{tr.sl} = h_{tr}(b_{tr} + h_{tr} \cdot ctg\alpha_{tr}),\ \text{m}^2, \tag{8}$$

where h_{tr} is the trough depth, m, h_{tr} = 5 – 1.5 m; b_{tr} is the trough bottom width, m; α_{tr} is an inclination angle of the trough slopes, deg (65 – 75°).

To prevent jamming of mined mass pieces during their movemen, the trough width is taken provided that:

$$b_{tr} \geq 3d_{\max}, \text{ m.} \tag{9}$$

Taken into account the maximum size of the mined mass overall piece, the trough width is taken as b_{tr} = 4 m.

Having calculated the cross-sectional area, which is $S_{tr.sl}$ = 5.1 m^2, it is possible to determine the trough length and its volume, but it is necessary to take into account the height of the rock chute lower part (h_{sl} = 10 m), to which the chute is formed.

The trough length:

$$l_{tr.sl} = \frac{H_{sl} - h_{sl}}{\sin\beta}, \text{ m.} \tag{10}$$

The trough volume:

$$V_{tr.sl} = S_{tr.sl} \cdot l_{tr.sl}, \text{ m}^3. \tag{11}$$

The calculation yielded values for the length and volume of the trough: $l_{tr.sl}$ = 52.6 m, $V_{tr.sl}$ = 268 m^3.

The structural parameters of the trough are presented in Fig. 5.

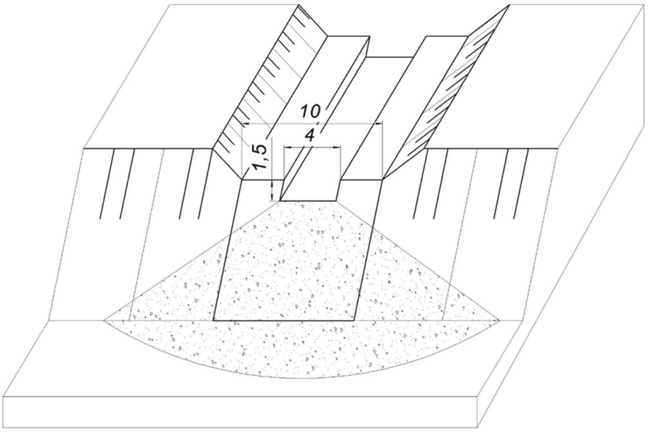

Fig. 5. Design of the rock chute trough.

It is important to determine the maximum volume of the temporary storage facility for the mineral, which should be located on the receiving platform of the rock chute. The lower platform parameters are calculated based on the overall dimensions of the mining-loading equipment [20 – 22]. For calculation, it is important to consider the required mined mass volume that needs to be placed in the storage facility. By limiting the height of the embankment under the rock chute h_n, and the average volume of the mined mass prepared by blasting (A_{bl}), the required area of the platform can be calculated.

Provided that blasting operations in the Rybalsky Quarry occur once a week, where the volume of A_{bl} is approximately 6 thousand m^3, the required area of the platform can be determined by the formula:

$$S_{pl} = \frac{3 \cdot A_{bl}}{h_{sl}}, \mathrm{m}^2. \quad (12)$$

With S_{pl} = 1800 m^2, calculate its length and width, which are: L_{pl} = 45 m, W_{pl} = 40 m. Design scheme of the rock chute is presented in Fig. 6.

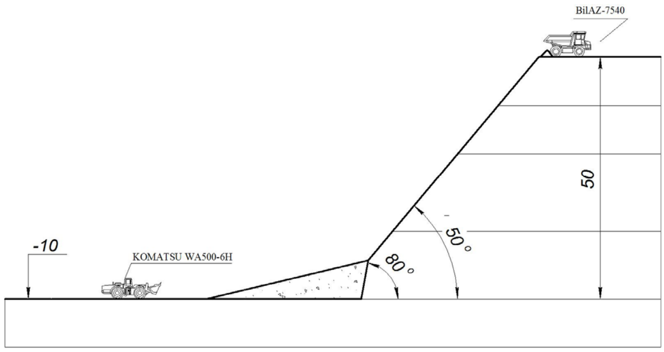

Fig. 6. Design scheme of the rock chute.

5 Conclusions

The paper conducts the research on improvement of technological scheme for mining the Rybalsky Granite Quarry.

It has been determined that the perspective technological scheme for mining granites is the use of automobile-gravity transport with rock chutes for moving mined mass from the upper horizons to the crushing-screening complex located at the bottom of the quarry.

Research has found the dependence of the cost for moving a mineral on the transportation distance, which allows determining the area of effective use of automobile and automobile-gravity transport using a rock chute.

The dependence of the effective slope angle of the rock chute on the friction coefficient during the mined mass movement has also been determined, due to which it is possible to set the effective slope angle of the rock chute for the conditions of the Rybalsky Quarry, which is 50º.

Economic efficiency from the implementation of rock chutes in the Rybalsky Quarry will reduce the mineral transportation cost by 45.8%, as well as gain an additional profit of 795 thousand UAH/year.

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