eISSN 2500-0632
https://mst.misis.ru/

MINING ROCK PROPERTIES. ROCK MECHANICS AND GEOPHYSICS

Research article

https://doi.org/10.17073/2500-0632-2022-2-137-149

Controlling blast energy parameters to ensure intensive open-pit rock fragmentation

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Abstract

Controlling blast action, in order to increase its energy efficiency in a production blasthole is quite an important issue. This is because it enables the formation of broken rock mass with preset coarseness parameters. Increasing the blast pressure and the time of the blast impact on a rock mass is traditionally recommended as one of the ways to improve the blast action on the rock mass, thus reducing the oversize yield in open pits. One device which enables this approach to a certain extent is a turbulator. The turbulator is fabricated of aluminum plate twisted in a helical fashion around its longitudinal axis. It is mounted in a production blasthole according to a specially designed scheme. The methodology developed to study the stress and strain state of a rock mass when using a turbulator in a blasthole explosive charge allows the size of radial fracture zone and the radius of rock fragmentation to be defined. A method was developed to initiate blasthole charges in a pit blasting block. It includes drilling blastholes, filling them with explosive, installing downhole blasting caps, and blasting using non-electric initiation system. A blasting block is divided into two equal parts (sections), which in turn contain three series of blastholes for short-delay blasting. Blasthole charges are initiated simultaneously in the two parts of the block based on a trapezoidal blasting pattern, thus ensuring meeting detonation waves. In the first series, instantaneous blasting of blastholes located on both ends of the blasting block and forming a trapezoid (in plan view) is carried out. Then after 42 ms, the second series of blastholes (also forming a trapezoid) is detonated. After another 42 ms, the remaining blastholes are detanoated along the perimeter of the blast block in the third series. Implementation of this design with the effect of turbo-blasting for rock fragmentations by blasthole charges at the Kalmakyr deposit of JSC "Almalyk Mining and Metallurgical Complex" has led to the reduction of consumption of explosives, volume of drilling, secondary fragmentation costs, and increased productivity of excavators and mining safety.

Keywords

mining, open pit, blasting, explosives, rock fragmentation, turbo-blast, turbulator, blasthole charges, initiation, JSC "Almalyk Mining and Metallurgical Complex", JSC "Navoi Mining and Metallurgical Complex", Uzbekistan

Acknowledgments

The research was performed within the framework of the Plan of Applied Research Works of Navoi State Mining Institute on the topics: "Development of the technology for forming stable open pit walls with regard to drilling and blasting operations technique" (Project No. BV-Atekh-2018-37).

For citation

Nasirov U.F., Zairov Sh.Sh., Mekhmonov M.R., Fatkhiddinov A.U. Controlling blast energy parameters to ensure intensive open-pit rock fragmentation. *Mining Science and Technology (Russia)*. 2022;7(2):137–149. https://doi.org/10.17073/2500-0632-2022-2-137-149

СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Управление параметрами энергии взрыва для обеспечения интенсивного дробления горных пород на карьерах

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Аннотация

Управление действием взрыва на основе повышения его энергетической эффективности в технологической скважине является актуальной задачей, так как позволяет обеспечить формирование разрушенной горной массы с заданными параметрами крупности. Одним из направлений повышения эффективности взрывного воздействия на горную породу и снижения выхода негабаритов на карьерах традиционно рекомендуется усиление взрывного давления и увеличение времени воздействия взрыва на массив горных пород. Одним из устройств, использование которого позволяет в определенной степени реализовать этот подход является турбулизатор. Турбулизатор изготавливают из алюминиевой пластины, скрученной винтообразно вокруг продольной оси. Монтаж устройства в взрывной технологической скважине осуществляют по специально разработанной схеме. Разработанная методика исследования напряженно-деформированного состояния горного массива при использовании конструкции турбулизатора в скважинном заряде взрывчатых веществ позволила определить размер зоны радиальных трещин и радиус дробления горных пород. Рекомендуется способ инициирования скважинных зарядов взрывчатых веществ во взрывном блоке карьера, включающий бурение взрывных скважин, заполнение их взрывчатым веществом, установление внутрискважинных капсюлей-детонаторов и взрывание неэлектрической системой инициирования. Взрывной блок разделяется на две равные части, которые в свою очередь содержат три серии скважин для короткозамедленного взрывания. Инициирование скважинных зарядов производится одновременно в двух частях блока в виде трапециевидной схемы взрывания с обеспечением встречи детонационных волн. В первой серии с двух концов взрывного блока производится мгновенное взрывание скважин в виде трапеции. Далее во второй серии через 42 мс взрываются последующие скважины также в виде трапеции. Еще через 42 мс по периметру взрывного блока в третьей серии взрываются оставшиеся скважины. Внедрение конструкции с использованием эффекта турбовзрывания при дроблении горных пород скважинными зарядами на месторождении Кальмакыр АО «Алмалыкский горно-металлургический комбинат» позволило снизить потребность во взрывчатых материалах и уменьшить объёмы бурения, снизить затраты на вторичное дробление, повысить производительность работы экскаваторов и безопасность горных работ.

Ключевые слова

добыча полезных ископаемых, карьер, взрывные работы, взрывчатые вещества, разрушение горных пород, турбовзрыв, турбулизатор, скважинные заряды, инициирование, АО «Алмалыкский горно-металлургический комбинат», АО «Навоийский горно-металлургический комбинат», Узбекистан

Финансирование

Исследование выполнено в рамках плана прикладных научно-исследовательских работ Навоийского государственного горного института на темы: «Разработка технологии отстройки устойчиво-конструктивных бортов карьеров с учетом технологии ведения буровзрывных работ» (проект №БВ-Атех-2018-37).

Для цитирования

Nasirov U.F., Zairov Sh.Sh., Mekhmonov M.R., Fatkhiddinov A.U. Controlling blast energy parameters to ensure intensive open-pit rock fragmentation. *Mining Science and Technology* (*Russia*). 2022;7(2):137–149. https://doi.org/10.17073/2500-0632-2022-2-137-149

Introduction

There are three main approaches to influencing the mechanical effect and controlling rock fragmentation, among known modern blasting optimization techniques [1, 2]:

1) the development of a rational design of explosive charge for effective rock mass fragmentation;

2) the observance of the principle of energy correspondence between the energy expended on rock fragmentation and the energy concentrated in an explosive charge unit;

3) the development of different blasting techniques.

A review of the current condition of drilling and blasting operations, taking into account the regularities of changing rock mass explosiveness [2-7], showed that drilling and blasting performance in these conditions can be improved. This can be achieved by defining the main regularities of the drilling and the effect of blasting parameters on physical-and-mechanical and mining properties of a rock mass, which change with the development depth, and on rock mass fragmentation performance. Other important factors to be defined include the justification of drilling and blasting parameters when using explosives to provide increased blasting performance and safety; the development of efficient blasting methods to improve rock mass fragmentation quality; the development of an integrated safety system for the production and use of explosives, as well as the development of technical and process solutions aimed at controlling blast action based on experimentally established physical phenomenon of increasing its energy and impulse in a blasthole.

At present time even the use of progressive methods of drilling and blasting does not enable the complete elimination of coarse fractions yield (oversize), as evidenced by the experience of breaking hard and very hard rocks in mining operations [8]. The increase of oversize yield from 2.5 to 5 % was found to lead to a reduction in excavator productivity by 20–30 %, while 20 % oversize yield reduces productivity 2.0–2.5 times [9–11]. Special attention should thus be paid to the solution of problems of improving rock mass fragmentation quality and ensuring decrease in oversize yield.

The traditional technique of blasting at deep levels of open pits has run its course. Therefore, more advanced methods need to be implemented, in order to fully ensure the preset quality of rock mass fragmentation. The current techniques for blasting rock mass fragmentation do not provide uniform fragmentation. This leads to a deterioration in rock mass preparation quality and increases excavation costs. When studying the processes of blasting rock mass fragmentation with the use of blasthole explosive charges, special attention needs to be paid to the physical features of their fragmentation depending on the specific structural and strength properties of a blasted rock mass. The use of turbo-blast phenomenon is the most promising area in creating methods of rock fragmentation with asymmetric spatial distribution of blast energy and its maximum concentration depthward a rock mass to be fragmented.

1. Study of the effect of “turbo-blast” in rock fragmentation with blasthole explosive charges

In order to increase the efficiency of blast action on a rock mass and reduce oversize yield in open pits, it is recommended to increase the action pressure and time by using a turbulator, the effect of which is described in detail in [12]. A turbulator is designed to increase the actual coefficient of utilization of the potential energy of a commercial explosive column charge. This is achieved by means of increasing the rate of secondary chemical reactions of an explosive afterburning in a blasthole after the detonation wave passage, until the detonation products reach the free surface.

The basic design of a turbulator is a plate made of steel or aluminum sheet, twisted helically around its longitudinal axis [12] (Fig. 1).

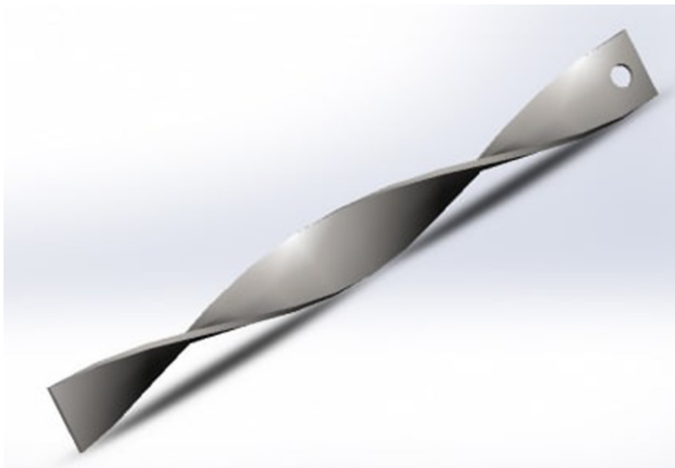

Fig. 1. Basic turbulator design [12]

Turbulator actuation by a detonation wave is presented in Figure 2 [12].

According to Fig. 2, in blasthole 1, detonation of intermediate detonator 2 in explosive 4 forms detonation wave 5 moving toward turbulator 6. The detonation wave passing through the helical plate moves further along the charge – 4.

The detonation wave passing along the turbulator causes turbulization effect. Fig. 2, b shows the resulting pressure at the detonation wave front.

In the turbulator, the pressure and velocity head of high-density detonation products moving behind the wave front arise.

The detonation wave is divided into force components F_x and F_y, whereby the component F_x creates torque around the longitudinal axis of the turbulator, imparting a rotational motion impulse. The component F_y imparts a translational motion impulse along the blasthole to the turbulator. As a result, high-speed rotational-translational motion begins as the detonation wave passes through the turbulator along blasthole *7*.

The high-speed rotational-translational motion causes axisymmetric *8* and longitudinal *9* vortex flows of explosive gases in the blasthole. In front of the turbulator, a gas compression zone arises (zone *10*), and behind it, a depression zone (zone *11*) due to the injection of explosive gases depthward the blasthole. The vortex flows *9* tear off finely dispersed particles (PM) of fragmented rock *17* from the blasthole wall *12* (Fig. 3). The flows are formed in zone *18* due to the blast shattering effect. The PM (particulate matter) concentration decreases towards the blasthole walls and increases towards the blasthole axis. Further, the explosive gases penetrate into the fractures in rock mass *19* [12].

Let us consider the hydrodynamic theory of detonation and shock wave propagation along a turbulator according to the schematic shown in Fig. 4.

Let us assume the following parameters of the medium in front of and behind the shock wave front: pressure P_0 and P_1, density ρ_0 and ρ_1, and temperature T_0 and T_1. We will use the laws of conservation of mass, momentum, and energy to find the relationship between these parameters.

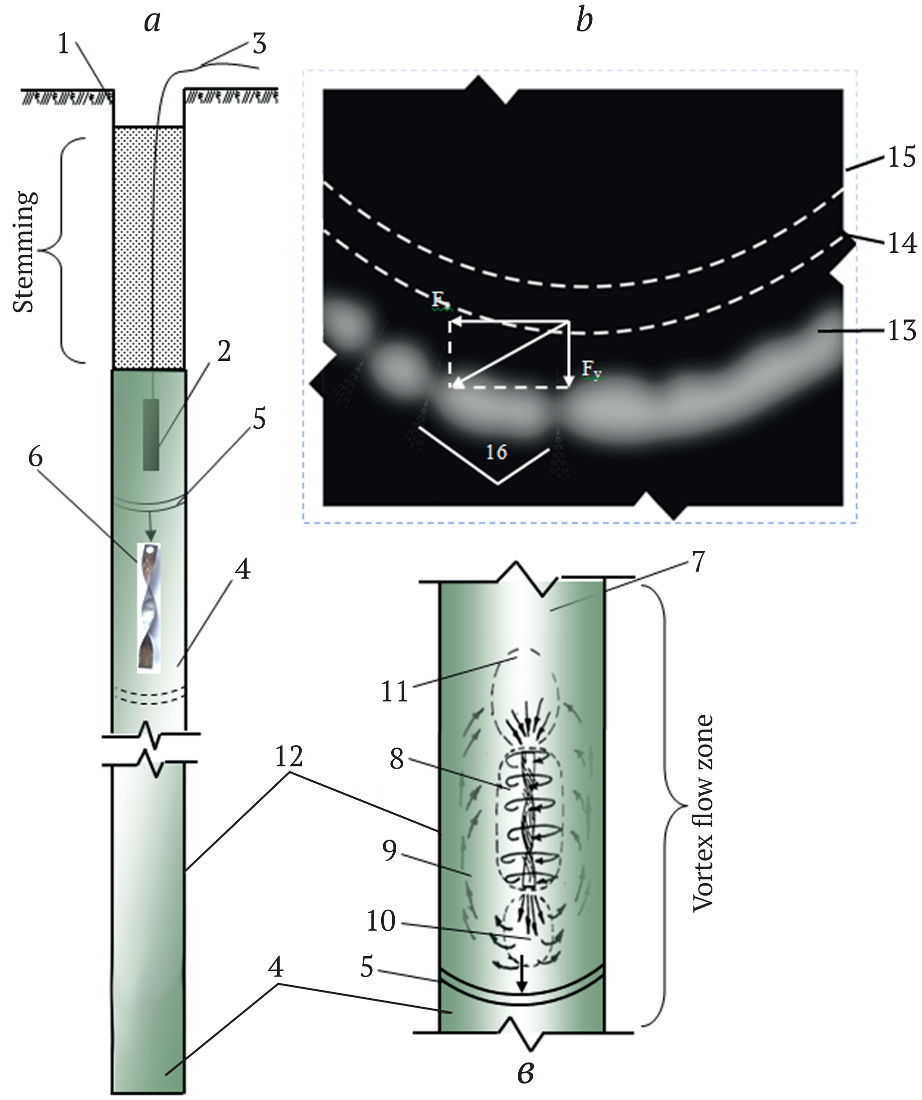

Fig. 2. Schematic of detonation wave action when using a turbulator [12]:
1 – blasthole; *2* – intermediate detonator; *3* – non-electric detonation system SINV; *4* – explosive charge column; *5* – detonation wave; *6* – turbulator; *7* – high-speed translational-rotational motion of a turbulator along a blasthole; *8* – axisymmetric vortex flows of explosive gases; *9* – longitudinal vortex flows of explosive gases; *10* – zone of gas compression; *11* – zone of gas depression; *12* – blasthole wall; *13* – bow shock wave front; *14* – estimated position of the contact surface; *15* – design position of the return wave in the DD; *16* – jets of detonation products penetrating the plasma

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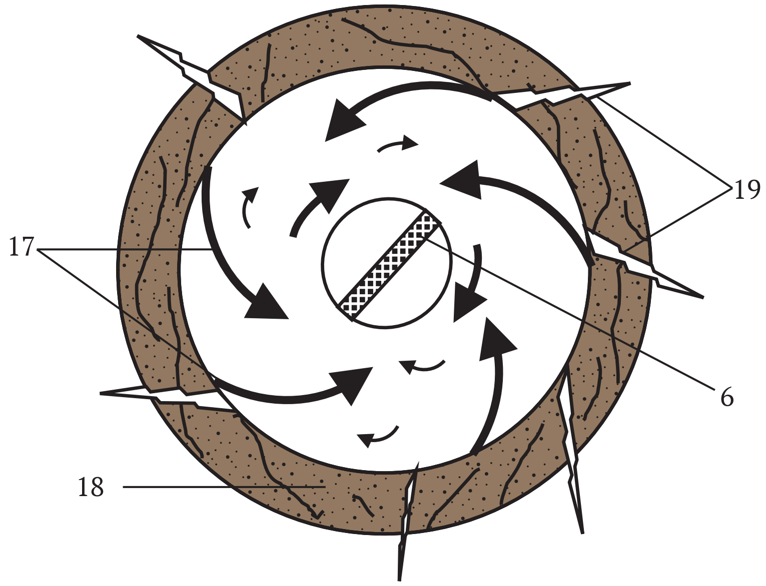

Fig. 3. The process of explosive gas vortex flow formation in a blasthole when using a turbulator:
17 – rock PM; *18* – zone of blast shattering effect; *19* – rock mass fractures

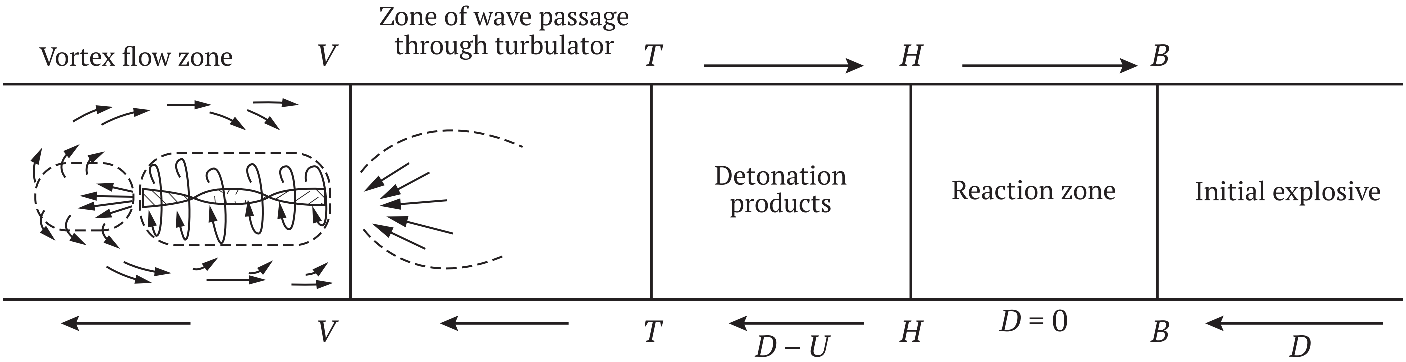

Fig. 4. Scheme of shock wave propagation along a turbulator

During time t the shock wave moves to distance Ut, and the shock wave front moves to distance Dt. The mass of the detonation wave compressed during this time is $\rho_1(D - U)St$, Before compression, the mass was equal to the product $\rho_0 DtS$. From the law of conservation of mass,

$$\rho_0 DSt = \rho_1 (D - U)St, \quad (1)$$

or

$$\rho_0 D = \rho_1 (D - U), \quad (2)$$

where ρ_0 is the detonation wave density before compression, kg/m^3; ρ_1 is the detonation wave density after compression, kg/m^3; D is the initial explosive detonation velocity, m/s; U is the detonation velocity after passing through a turbulator, m/s.

The change in the mass impulse is equal to the impulse of the force acting on it:

$$(P_1 - P_0)St = \rho_0 DStU, \quad (3)$$

or

$$P_1 - P_0 = \rho_0 DU, \quad (4)$$

where P_0 is the initial pressure of gases inside a blasthole, MPa; P_1 is the pressure of gases inside a blasthole after passing through a turbulator, MPa.

Since the process is considered adiabatic, the change in the total energy of the detonation wave mass $\rho_0 DSt$ is equal to the sum of the work of external forces and the energy after passing through a turbulator, i.e.

$$\rho_0 DSt = P_1 USt + E_r + E_{tr}. \quad (5)$$

Let us denote the internal energy of a unit of mass of the detonation wave before and after compression by ε_0 and ε_1, respectively, and the kinematic energy of a unit of mass after compression by $mU^2/2$.

Then:

$$\rho_0 DSt\left(\varepsilon_1 - \varepsilon_2 + \frac{mU^2}{2}\right) = P_1 SUt + E_r + E_{tr}, \quad (6)$$

where E_r is the rotary motion energy, J; E_{tr} is the translational energy, J; S is the blasthole cross-sectional area, m^2.

Let us define the mechanical stress on a blasthole walls when using a turbulator according to the scheme shown in Fig. 5.

We will define the detonation wave length and rotation velocity by means of the following formulas:

$$\Delta S = \alpha R; \tag{7}$$

$$v = \lim_{\Delta t \to 0} \frac{\Delta S}{\Delta t} = \frac{\Delta S}{\Delta t}; \tag{8}$$

$$v = \frac{d(\alpha R)}{dt} = \frac{R d\alpha}{dt} = R\omega, \tag{9}$$

where ΔS is the detonation wave rotation length, m; α is the turbulator rotation angle, deg; R is the turbulator torsion radius, m; v is the detonation wave rotation velocity, m/s; ω is the rotation frequency, Hz; t is the rotation time, s.

We will use a well-known formula for determining kinetic energy, in order to determine rotational and translational motion energies:

$$E_k = \frac{Mv^2}{2}. \tag{10}$$

It follows from equations (8)–(10) that the rotational velocity is equal to $v = R\omega$. Given this expression, we obtain the formula for determining rotational motion energy:

$$E_r = \frac{M\omega^2 R^2}{2}, \tag{11}$$

or

$$E_r = \frac{I\omega^2}{2}, \tag{12}$$

where I – is the moment of inertia, kg·m².

In formula (12) we will take into account the moment of inertia for a turbulator of length l and mass M, i.e. [13]:

$$I = \frac{1}{12} M l^2. \tag{13}$$

Hence the translational motion energy:

$$E_{tr} = \frac{M\omega^2 l^2}{24}. \tag{14}$$

Substituting expressions (11) and (14) into equation (7), we obtain the equality of the law of conservation of mass:

$$\rho_0 DSt\left(\varepsilon_1 - \varepsilon_0 + \frac{mU^2}{2}\right) = P_1 SUt + \frac{M\omega^2 R^2}{2} + \frac{M\omega^2 l^2}{24}. \tag{15}$$

The mechanical work of a blast in a blasthole when using a turbulator is determined by the formula:

$$A = P_1 SUt + \frac{M\omega^2 R^2}{2} + \frac{M\omega^2 l^2}{24}. \tag{16}$$

The mechanical stress on a blasthole walls is defined as:

$$\sigma = \frac{F}{S} = \frac{PS}{S} = P, \tag{17}$$

where F is the effective force, N; S – the cross-sectional area of a blasthole, m²; P – the mechanical pressure, MPa:

$$P = \frac{A}{\Delta V}, \tag{18}$$

where ΔV is the volume of rototraversingly moving gases, m³:

$$\Delta V = S\Delta l = S(D - U)t, \tag{19}$$

where Δl is the length of rototraversingly moving gases, m.

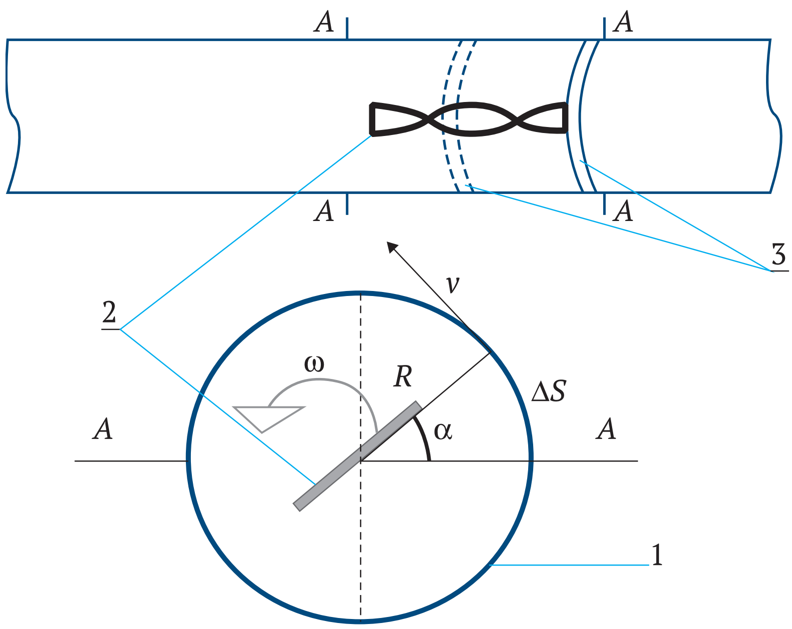

Fig. 5. Scheme for the calculation of mechanical stress on blasthole walls:
1 – blasthole; *2* – turbulator; *3* – detonation wave; *R* – turbulator torsion radius; α – turbulator rotation angle;
ω – detonation wave rotation frequency; *v* – detonation wave rotation velocity; Δ*S* – detonation wave rotation length

Substituting expressions (16), (17), and (19) into (18), we obtain a formula for determining the mechanical stress on a blasthole walls when using a turbulator:

$$\sigma = \frac{P_1 SUt + \dfrac{M\omega^2 R^2}{2} + \dfrac{M\omega^2 l^2}{24}}{S(D-U)t}. \quad (20)$$

We have thus determined the mechanical stress on a blasthole walls when using a turbulator. Implementation of the design with the effect of turbo-blasting for rock fragmentations by blasthole charges reduces the consumption of explosives, the volume of drilling, the secondary fragmentation costs, and increases the productivity of excavators and mining safety.

2. Determining the radial fracture zone size when using a turbulator in a blasthole explosive charge

On the basis of the theoretical assumptions from [14–17] the effect of the physical and mechanical properties of rocks and the explosives energy characteristics on the size of the rock fragmentation zone formed due to a blast when using a turbulator in a blasthole explosive charge was investigated. The mechanism of the fragmentation zone formation is shown in Fig. 6.

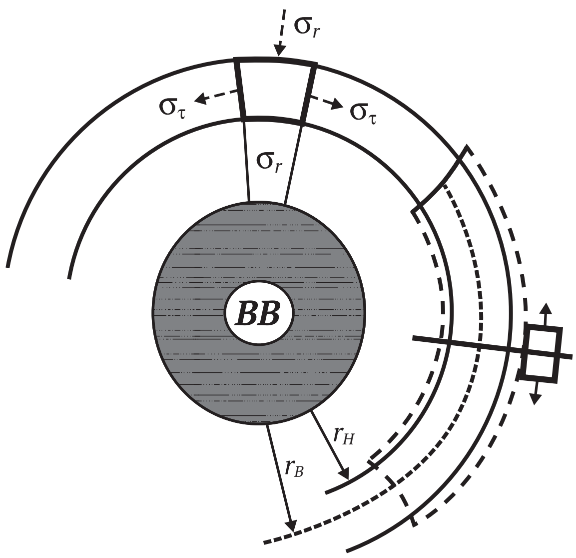

Fig. 6. Mechanism of fragmentation zone formation: σ_r – compressive stresses; σ_τ – tensile stresses

The flow of expanding gases as a result of turbulator action will move into fractures, thus promoting their opening. The expanding gases flow speed is rather high, and the gas in this case can reach the fracture tip. Due to the fact that the gas flow in the fractures is accompanied by hydrodynamic and thermal losses, the pressure will begin to rapidly decrease, becoming insufficient for further fracturing.

Thus, the size of the blast-caused radial fracturing zone will depend on the pressure and strength of the blast detonation products and the elastic properties of the rocks surrounding the charge.

Studies have shown that when using a turbulator in a blasthole explosive charge, the fragmentation zone size does not exceed 3–15 radiuses of the charge. In this regard, the radius of the radial fracturing zone will also depend on the explosive charge radius, the longitudinal wave propagation velocity in a rock mass, and stress.

The radius of the radial fracturing zone is determined by means of the formula [13]:

$$r_{rad} = r_0 C_p \frac{\sqrt{\gamma}}{5\sigma_{comp}}, \text{ m}, \quad (21)$$

where r_0 is the radius of explosive charge, m; γ the rock density, kg/m^3; C_p is the longitudinal wave velocity in a rock mass, m/s; σ_{comp} is the ultimate compression strength of a rock, N/m^2.

When using a turbulator in a blasthole explosive charge, the longitudinal wave velocity in a rock mass is determined taking into account the turbulator rotation angle. Hence

$$C_p = D \cdot cos\,\alpha, \text{ м/с}, \quad (22)$$

where D – is the velocity of detonation of an industrial explosive, m/s; α – is the turbulator rotation angle, deg.

It was found that the longitudinal wave velocity in the rock mass decreases with an increase in the turbulator rotation angle. For instance, at the turbulator rotation angle of 45o, the longitudinal wave velocity in the rock mass is 2,700 m/s.

It is recommended to determine the radial fracturing zone radius when using a turbulator in a blasthole explosive charge by means of the formula:

$$r_{rad} = \frac{0{,}2Dr_0\sqrt{\gamma}}{\sigma_{comp}} \cos\alpha, \text{ m}, \quad (23)$$

where D the detonation velocity of industrial explosive, m/s; r_0 is the radius of explosive charge, m; γ is the rock density, kg/m^3; σ_{comp} is the rock compressive strength, H/m^2; α is the turbulator rotation angle, deg.

3. Study of rock fragmentation process when using a turbulator in a blasthole explosive charge

According to the energy principle of drilling and blasting parameters calculation [17, 18], the quality of fragmentation, all other things being equal, is conditional on the explosive energy store in the rock mass volume to be fragmented. However, the blast energy can be used in different ways for rock fragmentation. The quality of rock fragmentation has been established to be dependent upon along with the explosive energy store, a number of factors. The most important of these are: rock mass fracturing; charge diameter; blasting pattern; interval, and order; as well as the charge design and type of stemming.

In view of the above, the dependence of the change in the average diameter of a piece of blasted rock mass d_i on the specific explosive consumption q (kg/m^3) when using a turbulator can be expressed as follows:

$$d_i = d_0 \exp(k_{\exp.en} d_0 q).$$

This formula allows for a dependence to be obtained, in order to define the distance between rows of blastholes and between blastholes in a row. This in turn allows the rock fragmentation radius when using a turbulator in a blasthole explosive charge to be determined, depending on the blasting conditions and the required quality:

$$r_{cr.rad} = \sqrt{\frac{pl_{ch}}{mH_l \frac{1}{k_{\exp.en} d_0} \ln \frac{d_0}{d_i}}}, \text{ м}, \quad (24)$$

where p is the capacity of 1 l.m. of blasthole, m; l_{ch} is the explosive charge length in a blasthole, m; m is the separation factor of blasthole charges; H_l is the bench height, m; $k_{\exp.en}$ is the factor taking into account the use of explosive energy for rock fragmentations at specific blast patterns; d_0 is the average diameter of rock mass block on the basis of blockiness (jointing) degree, mm; d_i is the average diameter of a blasted piece of rock, mm.

4. Development of a blasting rock mass fragmentation method with the use of a turbulator

A method of blasting rock mass fragmentation with the use of a turbulator has been developed. The method provides uniform and high-quality blasting rock mass fragmentation, as well as increasing the actual explosive charge potential energy efficiency by means of changing the mechanism of its transmission and increasing the fragmentation process duration.

According to this method, an aluminum plate 2×20×180 mm is twisted in a helical manner around the longitudinal axis by 360° (in a single turn). The plate is mounted vertically in the center of a polyvinyl chloride tube 180 mm long and 100 mm in diameter. Then the tube is sealed at both ends. This creates a device referred to as a turbulator in an air cavity (Fig. 7).

Then blastholes are drilled in the rock mass to be blasted according to a blasting pattern. At the bottom of each blasthole, an intermediate detonator is installed and a small amount of industrial explosive is inserted to completely cover the intermediate detonator (Fig. 8). Then a turbulator is placed into each blasthole and the blastholes are filled with the remaining amount of the explosive, and blasthole stemming and blasting is performed.

Applying the method of blasting rock mass fragmentation with the use of a turbulator enables uniform and high-quality blasting rock mass fragmentation. It also increases the actual explosive charge potential energy efficiency by means of changing the mechanism of its transmission and increasing the fragmentation process duration.

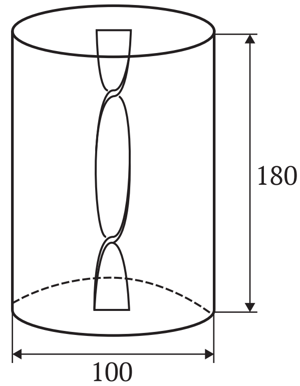

Fig. 7. Design of a turbulator in an air cavity made of PVC tube

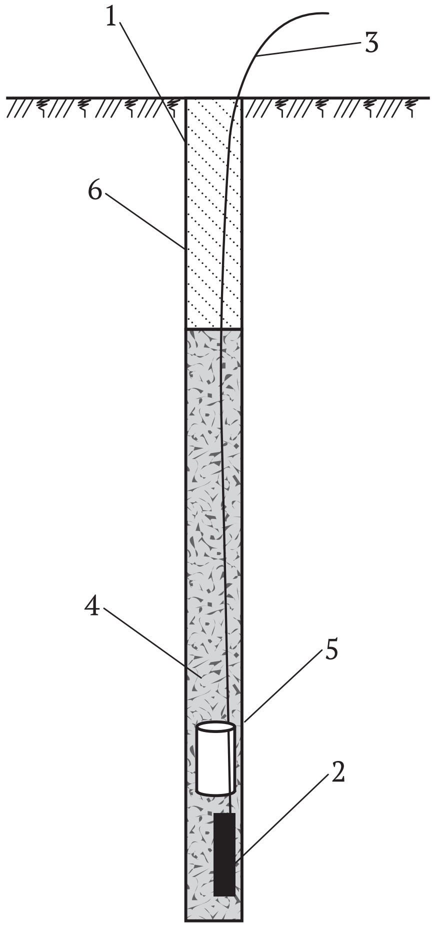

Fig. 8. Design of a blasthole explosive charge with a turbulator for rock mass fragmentation: *1* – blasthole; 2 – intermediate detonator; *3* – non-electric detonation system; *4* – industrial explosive; *5* – air cavity turbulator design; *6* – stemming

5. Development of a method of sectional blasthole initiation

A method of blasthole explosive charges initiation in a blasting block has also been developed. This allows for the duration, frequency, and orientation of blast load application to be regulated. It also increases blast energy utilization for rock fragmentation (Fig. 9).

This method provides for drilling rows of blastholes in a block to be blasted according to a blasting pattern. The blastholes are filled with an industrial explosive, and SINV non-electric detonation system is used for the blasthole charge initiation. The blasting block is divided into two equal parts (sections), and these, in turn, into three series of short-delayed blasting blastholes. The blasthole charges are initiated simultaneously in the two sections of the block based on a trapezoidal blasting pattern. This ensures that the detonation waves meet when moving toward each other simultaneously and provides collision of broken rock lumps. In the first series, the instantaneous blasting of blastholes located at both ends of the blasting block and forming a trapezoid (in plan view) is carried out. Then, after 42 ms, the second series blastholes (also forming a trapezoid) are blasted. In another 42 ms, the remaining blastholes are blasted along the perimeter of the blast block in the third series.

Applying this blasting method enables the effective utilization of blast energy and collision of moving rock lumps. This increases the energy consumption in rock fragmentation, provides preset fragmentation degree and a quality of rock mass preparation for different deposit development designs with minimal material and power consumption.

6. Industrial testing of the methods developed in order to improve the quality of rock mass fragmentation

In accordance with the “Program of research on redistribution of blast energy along the length of a blasthole charge when using the effect of turbo blasting” at Kalmakyr deposit of JSC “Almalyk Mining and Metallurgical Complex”, pilot tests were carried out. They used the new design of blasthole explosive charges with the turbo blasting effect and the method of blasthole explosive charges initiation in a blasting block.

The blasting tests were performed at “Yoshlik-I” open pit, located in the territory of Tashkent Region of the Republic of Uzbekistan at a distance of 1 km to the south of Almalyk city. The open pit produces copper-molybdenum ores. The pit rock mass excavation design capacity is 88.1 million m^3.

The main ore-bearing rocks at “Yoshlik-I” are syenite-diorite (58% of the estimated ore reserves), to a lesser extent diorite (35%), and granodiorite-porphyry (7%). The role of other rocks in the ore bodies’ location is extremely insignificant.

General characteristics of the ores and rocks:
– Protodyakonov hardness index – 10–15;
– Bulk density:
• balance and off-balance ores – 2.6 t/m^3;
• oxidized ore – 2.5 t/m^3;
• rock – 2.44 t/m^3;
– fragmentation index – 1.5;
– pit watering – 65–68%.

A SBSh-250MNA-32 drilling rig performed drilling of blastholes under the Program. ANFO explosive was used in blasting at the mine.

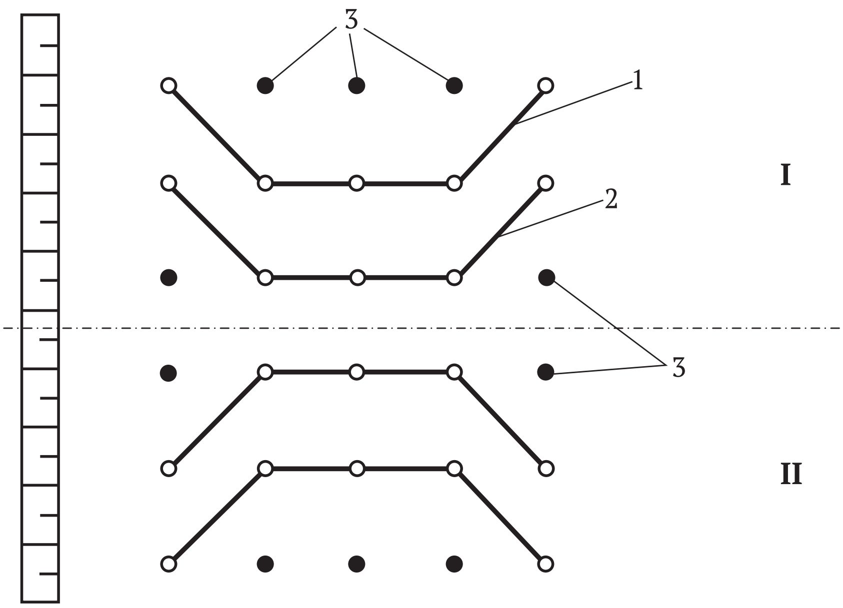

Fig. 9. Blasting pattern in the method of sectional blasthole initiation:
I and II – the first and second sections of blasting block; *1* – the first blasting series with no delay;
2 – the second blasting series with delay of 42 ms; *3* – the third blasting series with delay of another 42 ms

The parameters of the blasthole relieving (fragmentation) charges were calculated in accordance with the "Regulatory Guide for Drilling and Blasting" and "Technical Rules for Blasting on the Surface" [17, 18].

The parameters for the drilling and blasting when using the traditional and developed methods of blasting rock fragmentation are given in Table 1.

Table 1

Drilling and blasting parameters when using the traditional and developed methods of blasting rock fragmentation

Item	Value
Protodyakonov rock hardness index, *f*	10–14
Bench height, m	15
Drillhole depth, m	18
Drillhole diameter, mm	244.5
Blastholes spacing, m x m	7x7
Number of blastholes, pcs.	65
Weight of explosive in a blasthole, kg	588
Explosive type	ANFO
Intermediate detonator type	Almanit
Volume of blasted rock mass, m^3	50,180
Explosive specific consumption, kg/m^3	0.76
Drilling specific consumption, m/m^3	0.0245
Drilling rig productivity, l.m./year	41,800
Quantity of intermediate detonators, pcs.	1

The method of blasting rock mass fragmentation with use of a turbulator was applied, in order to increase the efficiency of blast action on a rock mass and decrease the oversize yield. The use of this charge design changed the energy transfer mechanism allowing the fragmentation process time to be increased. The fragmentation process is determined by a primary compression wave and a system of subsequent stress waves, providing more uniform and high-quality rock mass fragmentation.

The scheme of sequential blasting of blasthole explosive charges with the use of a counter dynamic effect was industrially tested.

According to this scheme, 5 rows of blastholes of 252 mm in diameter were drilled in a blasting block at 5×5 m grid spacing by means of SBSh-250MN drilling rig. At a bench height of 15 m, the blasthole length was 17 m, the stemming length was taken at 5 m, and the charge length was 12 m. The blastholes were filled with ANFO industrial explosive with charge density of 0.85 g/cm^3. The mass of each blasthole charge was 618 kg.

Downhole blasting caps were installed at the bottom of the blastholes (one blasthole – one blasting cap). Delay intervals between the blasthole series were taken at 0.42 ms and 84 ms. The detonation sequence was according to a trapezoidal scheme, ensuring the detonation waves meeting in the center of the blasting block. The initiation of charges in the SINV system was carried out by means of ED-8Zh electrical blasting caps and the main wire of DShE-12 detonating cord. SINV-START served as the source of the explosive pulse for the SINV non-electric detonation system.

The blasting block was divided into two equal sections, I and II with 15 blastholes in each section, and these, in turn, into three series of short-delayed blasting blastholes. Instantaneous blasting of blastholes forming a trapezoid (in plan view) was carried out simultaneously in sections I and II from both ends of the blasting block in the first series. Then, after 42 ms, the second series blastholes (also forming a trapezoid) were blasted. After another 42 ms, the remaining blastholes (the third series) were blasted along the perimeter of the blast block.

The main parameters characterizing the blasting results were the blasted rock mass PSD, and the oversize yield. The results of industrial blastings by means of the traditional (standard) and developed methods are shown in Figs. 10 and 11.

After each blast the broken rock PSD was analyzed while handling. Comparative PSD data for the traditional and developed methods are shown in Table 2 and Fig. 12.

Table 2

Comparative PSD data for the traditional and developed methods of rock fragmentation

Linear size of fractions *d*, mm	Shares of fractions depending on the method of rock fragmentation, %	
	traditional	developed
0–300	20	61.3
301–400	11	12.1
401–500	10	11.2
501–600	16	10.5
601–700	11	2.3
701–800	12	1.6
801–900	11	1
901–1000	5	–
above 1000	4	–

The particle size distribution (PSD) analysis showed that the method developed, when compared to the traditional one, reduced the average lump size by 43 % and the number of oversized lumps by 44 %. Pilot tests showed that the method developed provides uniform rock fragmentation.

Thus, the design with the effect of turbo-blasting in rock fragmentations by blasthole charges reduces the consumption of explosives, the volume of drilling, the costs for secondary fragmentation, while increasing the productivity of excavators and mining safety. Implementing the developed method of sequential

Fig. 10. Results of industrial blasting by means of the traditional rock mass fragmentation method

Fig. 11. Results of industrial blasting by means of the developed rock mass fragmentation method

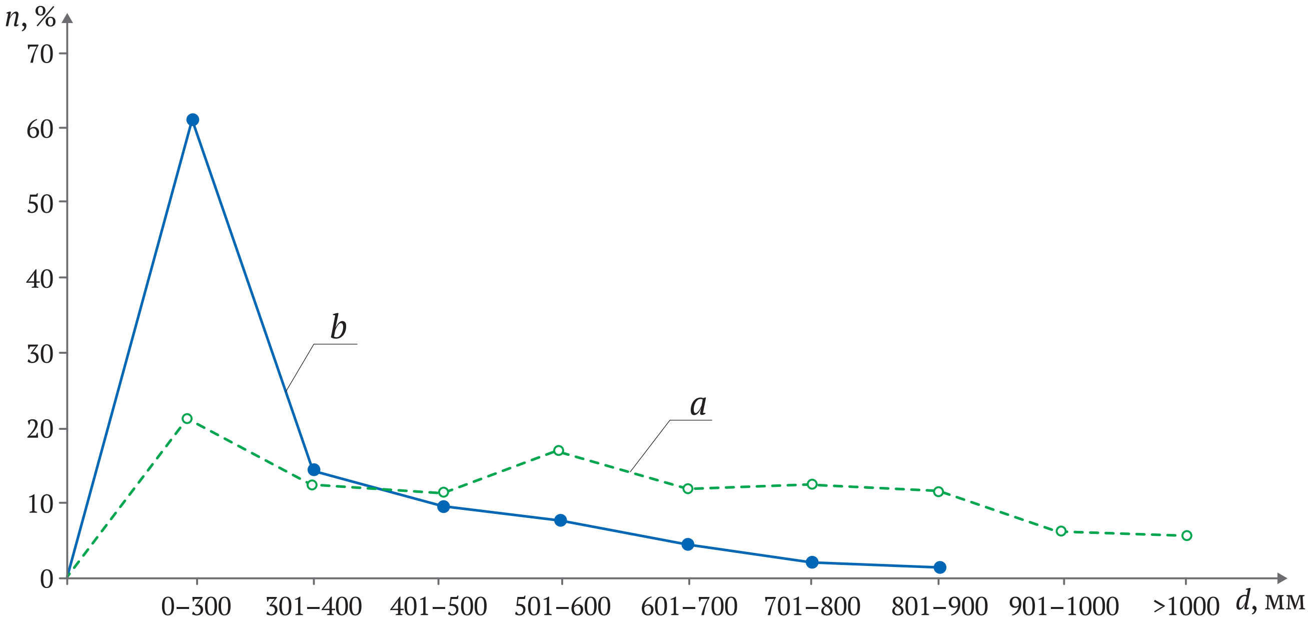

Fig. 12. PSD in the traditional (*a*) and developed (*b*) methods of rock fragmentation

blasting of blasthole explosive charges with the use of the counter dynamic effect enabled effective utilization of blast energy and collision of moving rock lumps. This increased the blast energy consumption in rock fragmentation, and provided preset fragmentation degree and quality of rock mass preparation with minimal material and power consumption.

Conclusions

1. One of the most important components in open-pit mining of mineral deposits is blast action control. This requires a proper understanding of the physical mechanism of the blast effect on a rock mass to be fragmented. Increasing the action pressure and time by means of a turbulator is recommended, in order to improve the efficiency of a blast action on a rock mass and decrease the oversize yield in open pits. A turbulator is designed to increase the actual coefficient of utilization of the commercial explosive column charge potential energy. This is achieved by increasing the rate of secondary chemical reactions of the explosive afterburning in a blasthole after the detonation wave passage until the detonation products reach the free surface.

2. The proposed mathematical model of blast energy redistribution along the length of a blasthole when using the effect of "turbo-blasting" shows how the degree of blast action on a rock mass can be optimized via redistribution of blast energy along the explosive charge length. The mechanical pressure on the walls of a blasthole depends on the following factors: the pressure behind the shock wave front; the blasthole cross-sectional area; the detonation velocity after passage through a turbulator; the shock wave passage time; the length and mass of the turbulator; the rotation frequency; the turbulator torsion radius; and the initial explosive detonation velocity.

3. The physical and mechanical properties of the rock and explosive energy characteristics have an effect on the size of the rock fragmentation zone formed due to a blast, when using a turbulator in a blasthole explosive charge. The size of the radial fracturing zone formed during a blast depends on the pressure of the blast detonation products and strength and elastic properties of the rocks surrounding the charge. The radial fracture zone radius when using a turbulator in a blasthole explosive charge varies in direct proportion to the charge radius, the industrial explosive detonation velocity, the blasted rock density, and the turbulator rotation angle and is inversely proportional to the rock ultimate compressive strength.

4. The method of blasting rock mass fragmentation with the use of a turbulator is recommended. The method provides for the uniform and high-quality blasting rock mass fragmentation, and also increases the actual explosive charge potential energy efficiency by changing the mechanism of its transmission, and increasing the duration of the fragmentation process. A method of blasthole explosive charges initiation in a blasting block is also recommended. This allows the duration, frequency, and orientation of blast load application to be regulated and the blast energy utilization for rock fragmentation to be increased.

5. Use of turbo-blasting for rock fragmentation by blasthole charges and the method of blasthole explosive charges initiation in a blasting block at the Kalmakyr deposit of JSC "Almalyk Mining and Metallurgical Complex" has reduced the consumption of explosives, the volume of drilling, secondary fragmentation costs, and increased the productivity of excavators and mining safety. The particle size distribution (PSD) analysis shows that the methods developed, when compared to traditional ones, reduced the average lump size by 43 % and the number of oversized lumps by 44 %.

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Received 02.02.2022
Revised 14.03.2022
Accepted 25.05.2022