IMPROVING THE ENERGY EFFICIENCY OF THE EXPLOSIVE PULSE DURING DRILLING AND BLASTING OPERATIONS TO INCREASE THE QUALITY OF CRUSHING AND CONDITIONS FOR CONVEYOR DELIVERY OF OVERBURDEN ROCKS IN QUARRIES AND SECTIONS

Tasbulat Monbolovich Igbaev[1], Nurlan Asylkhanovich Daniyarov[2], Adilbek Kazbekovich Kelisbekov[3,*], Arsen Zakirovich Akashev[4]

[1]NJSC Kokshetau University SH. Ualikhanov, Kokshetau, Republic of Kazakhstan
[2]Corporate University of Personnel Services of Kazakhmys Corporation LLP, Karaganda, Republic of Kazakhstan
[3]Department of Transport and Logistics Systems, NJSC Karaganda University named after. E. A. Buketov, Karaganda, Republic of Kazakhstan
[4]Department of Industrial Transport named after. Professor A. N. Daniyarov, NJSC Karaganda Technical University named after Abylkas Saginov, Karaganda, Republic of Kazakhstan

*E-mail of corresponding author: akelisbekov@mail.ru

Nurlan A. Daniyarov 0000-0002-4476-4569, Adilbek K. Kelisbekov 0000-0001-8857-8162, Arsen Z. Akashev 0000-0001-5316-4146

Resume
Widespread application of advanced transportation technologies in conditions of open-pit mining with the use of high-capacity belt conveyors is limited by the need for additional crushing of overburden rocks and minerals. Accordingly, the quality of crushing of rock mass, the output of oversize during drilling and blasting operations at quarries and open-pit operations significantly affect the possibility of using flow and cyclic-flow technologies with the use of conveyor transport. In this paper is presented a method of increasing the energy efficiency of the explosive pulse in drilling and blasting operations by means of developed gas pedal designs to improve the quality of crushing and conditions of conveyor delivery of rock mass.

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1 Introduction

An undeniable trend in the development of the mining industry for the foreseeable future is considered to be the stable orientation of the industry towards an open method of development as providing the best economic indicators. It accounts for up to 73% of the total volume of mining in the world. For example, in the Republic of Kazakhstan, 70% of thermal coal is extracted by open-pit mining, while the main consumers are power plants (70%), industrial enterprises (20%) and the private sector (10%). Open-pit coal mining in Kazakhstan is carried out at three giant deposits (Bogatyr, Severny and Vostochny sections) in the Ekibastuz basin (Pavlodar region) and at four deposits in the Karaganda region (Borlinskoye, Shubarkolskoye, Kushokinskoye and Saryadyrskoye). The total potential for extraction of projected open-pit coal reserves in the country is estimated at 400 million tons per year, and industrial reserves suitable for open-pit mining amount to 21 billion tons [1]. The development of an open-pit mining method, characterized by a combination of preparatory, stripping and mining workings in a quarry field, is accompanied by an increase in production concentration, an increase in depth, spatial dimensions of quarries and sections, distance and complexity of transporting rock mass. At the same time, the determining indicator is the depth of quarries; in particular, the depth of the eleven

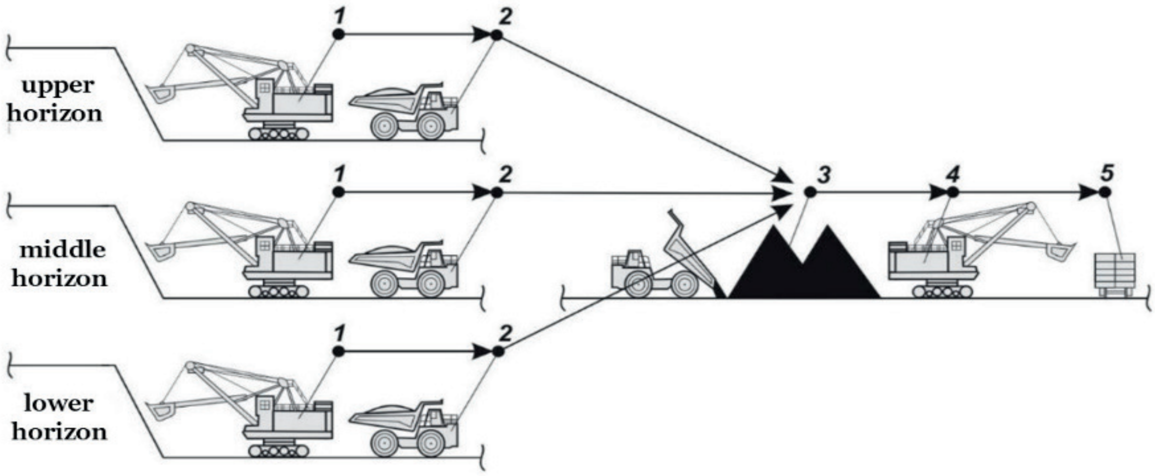

Figure 1 *Cyclic technology of coal mining at the Molodezhny section: 1 - mining excavators, 2 - BelAZ 75131 dump trucks, 3 - averaging warehouses, 4 - loading excavators, 5 - railway transport*

largest coal mines in Kazakhstan varies from 40 to 200 m.

The Molodezhny section of the Borlinsky deposit Kazakhmys Coal LLP uses the cyclic coal mining technology on three horizons - upper, middle and lower. The maximum depth of the incision is approximately 130-140 m. In the faces of mining horizons, coal is loaded by electric and hydraulic excavators into BelAZ 75131 dump trucks. Dump trucks deliver coal from the faces to the average warehouses, where it is loaded onto the railway transport, Figure 1 [2]. At the Bogatyr section, a flow-through technology for the development of minerals and overburden rocks has been implemented, including transshipment of the latter into the developed space, while rotary excavators in combination with conveyors provide an annual productivity of 50 million tons. In-line mining technology has also been introduced at the Vostochny coal mine: coal mining, transportation, averaging and shipment are carried out by four rotary complexes consisting of the SRs(k)-2000 rotary excavator, downhole and interstage loaders, connecting, lifting and main conveyors and an averaging and loading machine. For the excavation of overburden rocks, a cyclic flow technology has been introduced at the quarry, including the operation of two lines of the overburden complex, Figure 2 [3-4].

The active introduction of in-line and cyclic-in-line technologies in open-pit mining conditions is due to an increase in the depth of quarries, a progressive increase in their productivity, since cyclic technology with the delivery of rock mass by road and rail leads to a deterioration in technical and economic indicators due to an increase in the cost of production as a result of an increase in the cost of the transportation process [5]. In particular, according to the results of a number of studies conducted earlier at the Karaganda Polytechnic Institute (later - Karaganda State Technical University), it was found that when deepening a quarry for every 100 m, the cost of transportation for cyclic modes of transport increases by 1.5 times, and when using continuous modes by only 5-6% [6].

An analysis of the operation of technological equipment in open-pit mining shows that a third of the downtime is accounted for by transport due to its cyclical nature of work. In this research it was also found that the use of cyclic technologies in quarries is the most cost-effective at their depth of 150-250 m. When conducting open-pit mining operations at a depth of more than 250 m, it is economically feasible to use in-line and cyclic-in-line technologies [6].

2 Substantiation of the relevance of the problem

A characteristic feature of the use of in-line and cyclic-in-line technologies is the widespread use of conveyors, while the main type of these means of continuous transport currently in operation in quarries are belt conveyors. This is determined by their main design advantages over other types of conveyor systems - comparative simplicity of design and relatively low metal consumption. As the experience of operation shows, modern belt conveyors are capable of providing the high level of production for the largest quarries and sections, but, in general, they are suitable only for transporting loose and semi-hard rocks, and, most importantly, they are not able to move largesized loads of pieces larger than 600 mm, requiring crushing prior to transporting them, which leads to a significant increase in the cost of operating expenses [7-9].

This problem is especially relevant when transporting a large volume of overburden, the extraction of which, as a rule, is carried out in quarries by drilling and blasting. As a rule, the waste rock is

Figure 2 *Cyclic-flow technology at the Vostochny open-pit mine*

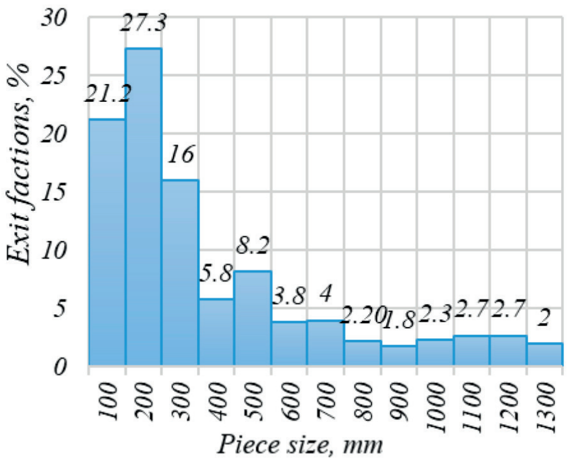

Figure 3 *Average fractional composition for 33 largest quarries based on the results of drilling and blasting operations*

too hard to be extracted without a certain number of explosions to grind the rock into smaller pieces, which can then be loaded onto a vehicle by excavators or other mechanical equipment. Figure 3 shows that the proportion of oversized material requiring additional crushing based on the results of drilling and blasting operations in quarries (with a piece size of 600 mm or more) is almost 20% of the total sample volume [10].

Thus, within the framework of implementation of cyclic-flow technology for the conditions of "Molodezhny" open-pit mine of Kazakhmys Coal LLP in Karaganda Technical University at the Department of Industrial Transport a promising technological scheme of delivery of rock mass, which can be used in the transportation of overburden and minerals in the case of increasing the depth of open-pit mining operations, presented in Figure 4: mining excavators - *1*, dump trucks BelAZ 75131 - *2*, chute for rock mass descent - *3*, intermediate averaging stockpile - *4*, bulldozer Chetra T-25 - *5*, receiving hopper NG - *6*, auger-tooth crusher SHZD - *7*, plate feeder - *8*, belt conveyors - *9-11*, waste rock dump or receiving hopper of the processing plant - *12* [11].

The rock mass from the upper and middle horizons is loaded into dump trucks BelAZ 7513, which deliver it to the chute for unloading into the receiving hopper; from the receiving hopper the rock mass flows by gravity through the chute to the site under the stack to the intermediate averaging yard. From the lower horizon, the rock mass is also loaded into dump trucks, which transport it to the averaging warehouse, from which it is shipped to the receiving hopper of the lower horizon by a Chetra T-25 bulldozer. The auger-tooth crusher, installed under the receiving hopper, crushes the mined rock mass; then it gets to the plate feeder, which transfers it further to the conveyor transport - belt conveyors, transporting it to the waste rock dumps or to

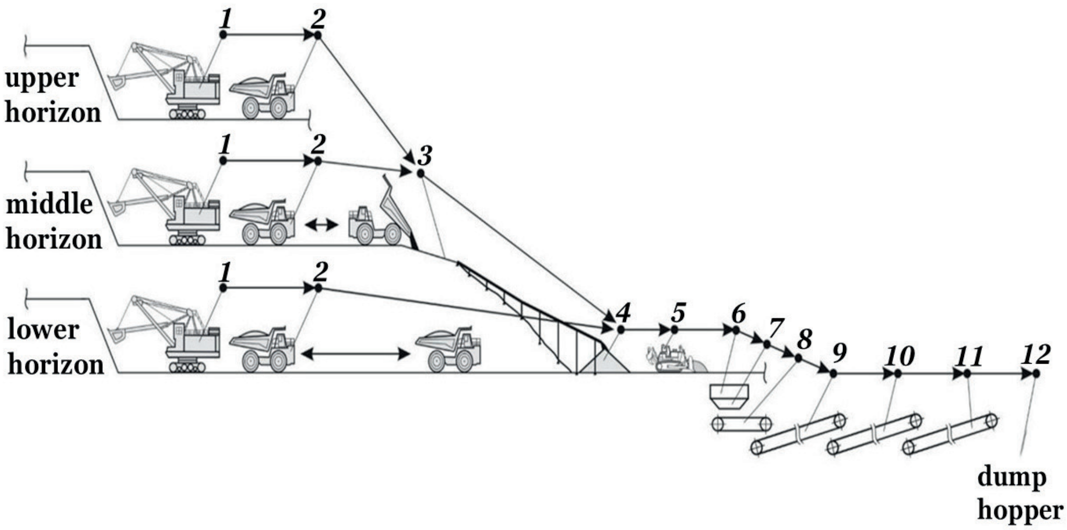

Figure 4 *Technological scheme of transportation using cyclic-flow technology at Molodezhny open pit mine of Kazakhmys Coal LLP*

the hopper of the enrichment plant. Table 1 shows the design parameters of belt conveyors, and Table 2 shows the general parameters of the conveyor line [11].

Estimated capital expenditures for implementation of this technological line also include costs for the purchase and construction of a crushing and reloading station, which, in particular, can be avoided by ensuring the necessary lumpiness of the rock mass extracted by the drilling and blasting method.

The lumpiness, quality of overburden rock mass crushing and oversize output during the blasting operations, as shown by the results of numerous studies, significantly affect the efficiency of application of flow and cyclic-flow technologies in open pit mining. To one of the first scientific researches in this direction belong the works of Baron, [12-13]. He systematized all the types of methods for measuring the lumpiness of rock mass in open pit and underground mining operations, based on the results of laboratory, polygon and production tests, analyzed various properties of explosives as criteria for their crushing ability in explosive rock removal [12-13].

In the work of Kolomnikov [14] the requirements for the coarseness of the transported material when controlling the energy of borehole charges, in the conditions of development at the mine “Muruntau” (Republic of Uzbekistan), using the cyclic-flow technology, are considered. The results of the complex research on improvement of ore crushing quality by borehole charges, based on consideration of physical and mechanical parameters of rock mass, are presented in the dissertation of Scherbich, G. V. Plekhanov St. Petersburg State Mining Institute, Russian Federation [15], which considered in detail the issues of optimizing the parameters of the drilling and blasting process to ensure a given degree of ore crushing. Optimization of blasting parameters by increasing the deceleration intervals is also presented in the work of Mityushkin et al. [16], in particular, multiple explosive loading of rock massif for a significant increase in the qualitative and quantitative indicators of the blasting process is considered.

The results of research on the control of explosion energy parameters to ensure intensive rock crushing at quarries are presented in the article by Nasirov et al. [17], which presents the experience of implementing the developed design using the turbo-explosion effect in rock crushing by borehole charges.

The influence of the detonation velocity of explosives on the degree of rock pre-destruction was considered in the work of Khokhlov et al. [18]: the issues of using explosives with reduced detonation velocity to reduce the intensity of predestruction in the zone of controlled crushing during the drilling and blasting process are presented.

One of the new publications on development of technologies aimed at improving the quality of rock crushing is a study on application of artificial intelligence and computer vision technologies to optimize the performance of the drilling and blasting complex at open-pit mining operations, Kovalchuk et al. [19]. In particular, the influence of the granulometric composition of the blasted rock mass on further stages of ore preparation was considered, the processes that affect the quantitative and qualitative indicators of the granulometric composition of the rock mass are determined.

Thus, as the analysis of the results of the above-mentioned studies, conducted within the framework of the development of methods and ways of intensification of all the processes of mining production, including loading and transportation operations, the issues of improvement and efficiency of the technology of explosive stripping, providing a given mode of crushing and compact bulk of the stripped rock mass, undoubtedly, acquire actual importance.

Table 1 *Design parameters of belt conveyors*

No. of conveyor in Figure 4	Length of the pack, m	Lift angle, deg
9	380	12
10	650	4
11	560	2

Table 2 *General parameters of the conveyor line*

No. n/a	Name	Significance
1	Hourly capacity of a conveyor line (estimated), tons/hour	1153.85
2	Hourly productivity of a conveyor line (accepted), tons/hour	1200
3	Density of cargo in loosened state, tons/m^3	1.24
4	Belt width (calculated), m	1.22
5	Belt width (accepted), mm	1400
6	Linear mass of the load on the conveyor, N/m	1308
7	Linear mass of rotating parts of the roller supports on the load branch of a conveyor, N/m	498.68
8	Linear mass of rotating parts of the roller supports on the idle branch of a conveyor, N/m	176.58

3 Theoretical basis of the study

The main phenomena accompanying explosive rebound during the mining operations - the explosion of an explosive charge in a destructible array are reduced to the following processes: detonation of the charge; expansion of the charging cavity by detonation products; mechanical interaction of detonation products with the destructible medium; propagation of shock waves and stress waves in rocks and, directly, the destruction of the mountain range. It has been established that a more uniform crushing of rocks is obtained by the explosion of borehole explosive charges with air gaps - this is explained by the interference of the shock waves, that is, a mutual increase in the resulting amplitude of waves formed during the explosion of various parts of the charge [20]. During the explosion of solid charges, as studies have shown, the rock, which is destroyed mainly due to compression forces, is crushed extremely unevenly, moreover, a large proportion of the explosion energy is spent on the re-crushing of rocks around the bottom of the charge. The separation of the charge column into separate parts and their simultaneous initiation contribute to the collision of detonation products at the locations of air gaps, which has a positive effect on the crushing of rocks.

The shape of the explosive charge also has a significant influence on the destructive effect of the explosion. In particular, it was found that using various forms of charge, or charges with recesses of various shapes (conical, spherical, parabolic, etc.), it is possible to create a cumulative effect, that is, to achieve a concentration of explosion energy that allows significantly enhancing the penetration effect of the charge on the mountain range by creating tensile and bending forces in it [21-23]. It was also found that the enhanced effect of the cumulative effect can also be obtained by placing dispersed cone-shaped caps on the detonating cord along the axis of the borehole charge. The overall effect of amplifying the explosion energy in this case is obtained from the cumulative effect of cumulative flows focused in the cone-shaped cavities into the bottom of the well, as a result of which the crushing of rock mass in the quarry is improved [24].

Determining the cumulative explosion pulses along the borehole formation presents significant difficulties because axial and radial expansion and various wave processes must be taken into account. The problem is simplified if the radial expansion of detonation products is neglected.

Explosions of charges with different shapes or notches give rise to complex wave processes associated with the collision of cumulative jets and gas flows from individual parts of the charge moving toward each other. The exact solution of the problem on the distribution of explosion parameters along the borehole in these cases is a rather complicated mathematical problem [25-26]. These difficulties are circumvented in various ways. For example, in the study of charges with air gaps, Baum et al. [27] and Baker et al. [28] propose to consider them as a solid charge, but with a greater height than that of a conventional charge at a lower density, and further, all the calculations should be carried out similarly to a solid charge. It is proposed to extend these assumptions for charges with different shapes of notches.

Let H_3 - be the height of a cylindrical charge, P_H - the initial pressure, C_H - the speed of sound in the detonation products before the onset of their expansion, and D - the diameter of the borehole. It is known that

$$P_H = \frac{1}{8}\rho_{cd} D^2,\ C_H = \sqrt{\frac{3}{8}D}\,, \tag{1}$$

where: ρ_{cd} - is the charge density.

Let x - denote the coordinate and t - denote the time of detonation product dispersal.

A rarefaction wave appears in the cross section $x = 0$ with the beginning of detonation product dispersal, which is described by the known equations of gas dynamics up to the time $t_1 = H_3/C_H$. When the isoentropic expansion of detonation products, $PV^3 = const$, is taken into account, they are of the form

$$x = (V - C)t + F(V),\ V + C = const\,, \tag{2}$$

where: V - is the detonation velocity,

Based on the boundary conditions: $t = 0$, $V = 0$, $x = 0$, $C = C_H$ one obtains: $F(V) = 0$, $C_H = const$.

Then, Equation (2) can be written in the form

$$x = (V - C)t,\ V + C = C_H\,. \tag{3}$$

Consequently, the expression $C = C_H - V$ is substituted into the first equation of the system of Equations (3) and V is found as:

$$V = \frac{x}{t} + C,\ V = \frac{1}{2}\Big(C_H + \frac{x}{t}\Big). \tag{4}$$

Thus, the solution of the system of Equations (2) can be written in the form

$$V = \frac{C_H}{2}\Big(1 + \frac{x}{C_H t}\Big), \tag{5}$$

$$C = \frac{C_H}{2}\Big(1 - \frac{x}{C_H t}\Big). \tag{6}$$

The pressure in the detonation products is determined from the relation

$$\frac{P_1}{P_H} = \Big(\frac{C_1}{C_H}\Big)^3 = \frac{1}{8}\Big(1 - \frac{X}{C_H t}\Big)^3. \tag{7}$$

At the moment of time $t = H_3/C_H$ the wave reaches the end of the charge, a new reflected rarefaction wave appears, the motion of which is described by the general equations of gas dynamics.

$$X = (V - C)t + F_1(V - C), \tag{8}$$

$$X = (V + C)t + F_2(V + C). \tag{9}$$

At the moment $t = H_3/C_H$ the velocity V becomes equal to 0, $x = H_3$, hence $F_1 = 0$ and

$$V - C = \frac{x}{t}. \tag{10}$$

In the section $x = -H_3$, at any moment of time $V = 0$, whence it follows that

$$F_2 = -H_3 - Ct\,. \tag{11}$$

Expressing $t = \frac{x}{V - C} = \frac{H_3}{C}$ from Equation (10) one finds:

$$F_2 = -2H_3 \text{ and } V + C = \frac{x + 2H_3}{t}. \tag{12}$$

The front of the reflected wave moves according to the law

$$\frac{dx}{dt} = V + C = \frac{x}{t} + \frac{2H_3}{t}. \tag{13}$$

Consequently, at $t = H_3/C_H, x = -H_3$ and $x = C_H t - 2H_3$.

Thus, the reflected wave front and the detonation product front propagate with the same velocity C_H.

Next, one has to find the pressure in the reflected wave. Taking into account that $C = H_3/t$ one obtains

$$\frac{P_2}{P_H} = \Big(\frac{C_2}{C_H}\Big)^3 = \Big(\frac{H_3}{C_H t}\Big)^3. \tag{14}$$

Equality (14) shows that the pressure in the reflected wave varies only in time. Knowing the distribution of pressure by time t and by coordinate x, one can write the total momentum:

$$J = \pi\, d_3 \int_{-H_3}^{x_2} \int_0^{\infty} P(x,t)dt\, dx\,, \tag{15}$$

where $x_2 = H_{hole} - H_3, H_{hole}$ - is the height of the hole (borehole).

Let the following dimensionless parameters be introduced as:

$$\tau = \frac{tC_H}{H_3}, \alpha = \frac{x}{H_3}, \overline{P} = \frac{P}{P_H}. \tag{16}$$

Then

$$J = \frac{tC_H}{\pi\, d_3\, H_{hole}^2\, P_H} = \Big(\frac{H_3}{H_{hole}}\Big)^2 \int_{-1}^{\frac{x_2}{H_3}} \int_0^{\infty} \overline{P}\, d\tau\, d\alpha\,. \tag{17}$$

Since

$$C_H = \sqrt{\frac{3P_H}{\rho_{cd}}} = \frac{\sqrt{6}}{4}D\,, \tag{18}$$

$$J = \Big(\frac{H_3}{H_{hole}}\Big)^2 \int_{-1}^{\frac{H_{hole}}{H_3} - 1} \int_0^{\infty} \bar{P}\, d\tau\, d\alpha\,. \tag{19}$$

next equation (19) is integrated first by α and then by τ and the final expression for the value of the total explosion impulse along the wellbore formation is obtained:

$$J = \frac{3}{8}\frac{H_3}{H_{hole}}\Big(1 + \frac{2H_3}{H_{hole}}\Big) - \frac{3}{16}\Big(1 - \frac{H_3}{H_{hole}}\Big)^2 \ln\frac{1 + \frac{H_3}{H_{hole}}}{1 - \frac{H_3}{H_{hole}}}. \tag{20}$$

Thus, the obtained equation reflects the correlation dependence between the parameters of explosive blasting and the structural values of the borehole and it can be used in solving problems of the penetration action of the cumulative jet and the distribution of specific explosion impulses along the borehole formation.

At the same time as experimental data show, determination of the influence of the blast wave impulse on the processes of rock mass crushing during the drilling and blasting excavation is possible only by modelling during the experimental studies, range or pilot tests in the conditions of real mining enterprises [29].

4 Experimental results

Analysis of the applied technologies of explosive stripping shows that in many cases the counter-impact of explosion products in air gaps is usually carried out at the detonation velocity of the explosive charge, which is insufficient to create a significant impulse and, accordingly, to increase the explosion energy acting on the massif to be destroyed to achieve the required lumpiness [30].

In this regard, the ideas outlined in the above works can be developed by pulsing an increase in the explosive charge explosion energy dispersed at intervals along the length of the charge. To do this, it is proposed to place the volumetric cavities of a special geometric shape (accelerators) in the explosive charge [31]. A sharp increase in the charge energy at the installation site of the cavity would take place if the explosive charge around the elongated cavity is initiated from its inner part over the entire surface simultaneously. In this case, a large mass and volume of explosives around a hollow volumetric cavity can be detonated. Modelling of explosive stripping processes with various forms of volumetric cumulative cavities was carried out in the laboratory conditions of the Department of “Rock Destruction by explosion” of the Moscow Mining Institute [30]. A mixture formed from building gypsum in various ratios with water and plexiglass was used as the test material (Table 3). As the material was being prepared, gypsum and water in the form of a mixture were poured into special molds and dried at room temperature. Samples of material with a thickness of 8 mm were prepared, the value of which was determined experimentally, taking into account the available amount of explosive to achieve the necessary cracking and crushing of the samples under consideration. The explosive charge in the thickness of the prepared material sample was formed using a PVC tube of an inner diameter of 3 mm. A constantan wire of a diameter of 0.3 mm was passed through the tubes, and then the tubes were filled with an explosive substance ammonite 6ZHV, giving them the shape of a cavity (Figure 5).

Each charge contained one cavity made of thick paper and filled with an explosive substance from the outside, which included sulfur and aluminum powder. The cavities were given various types of shapes: spherical; cones of different heights; cones connected by bases and ellipsoidal. The initiation of the explosive charge occurred as a result of passing a low-voltage current through a constantan wire. The process of explosive rebounding was recorded by high-speed photography. The actual distribution of the lumpiness of the destroyed sample on the laboratory model from the explosion of charges in various forms of the cumulative cavity is shown in Figure 6.

As a part of pilot tests, experimental explosions were carried out in the conditions of the Akzhal quarry of the Altaizoloto combine in the East Kazakhstan region with specially designed structures of one-, two- and three-cone volumetric cumulative cavities

Table 3 *Strength of samples after testing*

No. n/a	Gypsum to water ratio	Sample testing, MPa/mm		σ_c / σ_p
		for compression, σ_c	tensile, σ_p	
1	0.5 : 1	0.06	0.024	2.5
2	1 : 1	0.66	0.10	6.6
3	1.5 : 1	1.25	0.15	8.3
4	2 : 1	2.12	0.242	8.8

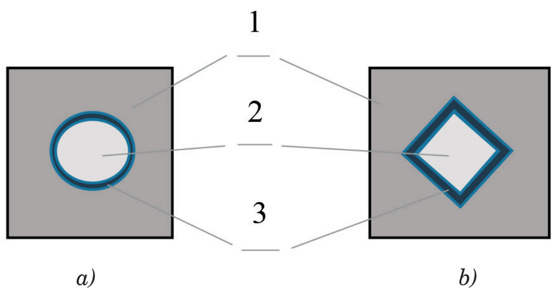

Figure 5 *Location of spherical shaped cavities in an explosive charge - a) and in the form of two cones connected by bases - b): 1 - gypsum sample, 2 - volumetric cavity, 3 - explosive charge*

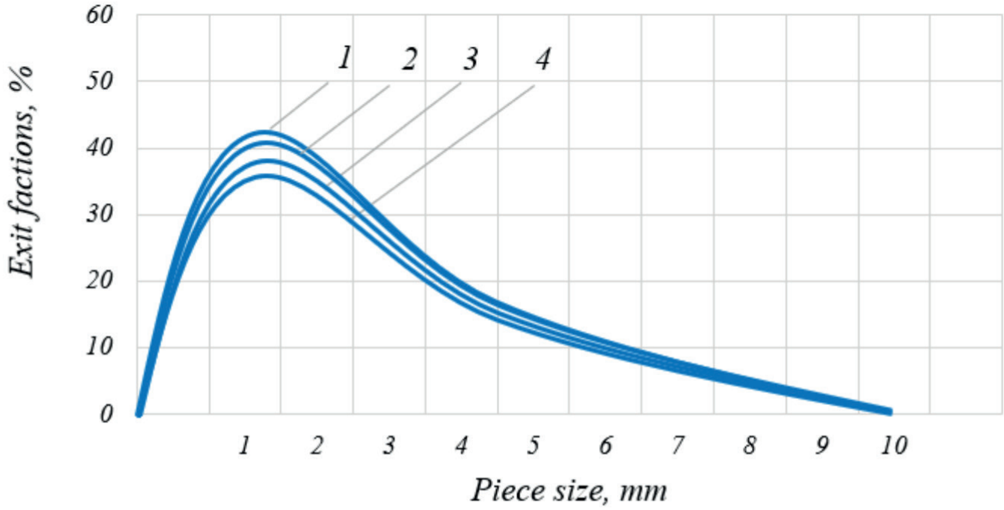

Figure 6 *Distribution of the lumpiness of the destroyed sample on a laboratory model with various shapes of the cumulative cavity: 1 - ellipse, 2 - cones connected by bases, 3 - cones of different heights, 4 - spherical shape*

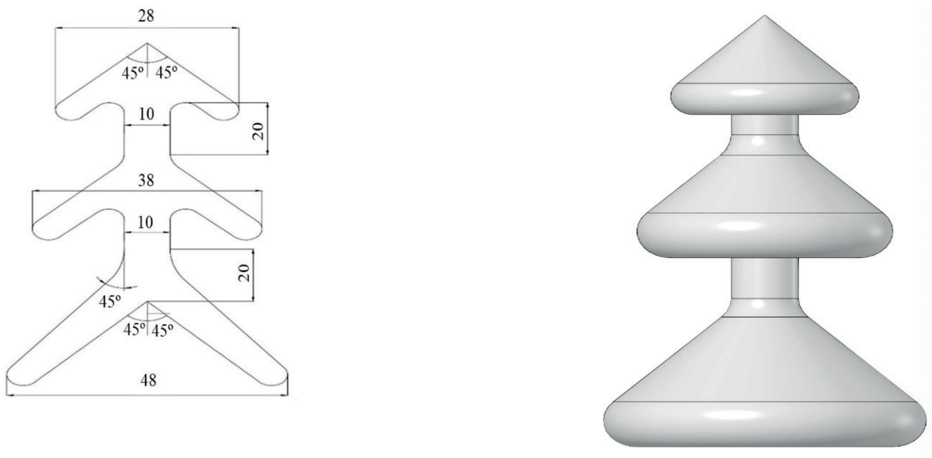

Figure 7 *Design of a three-cone cumulative cavity charge*

(accelerators) [31], Figure 7. The diameter of the wells was 150-250 mm, the depth was 3-5 m, the rock strength on the Protodyakonov scale was 13-15, the explosive used was grammonite 79/21.

The charge was formed as follows. An air partition 2, made of expanded polystyrene or polyethylene, was lowered into the well 1 (Figure 8), then a portion of explosive substance 3 was filled in, a three-cone accelerator 4 was lowered and a portion of explosive substance 3 was poured until the cavity was completely covered. Then the air partition 5 was lowered again, a portion of explosive substance 6 was filled in, a two-cone accelerator 7 was lowered and a small amount of explosive substance was poured. In the upper part of the well, similar operations were performed with a single-cone accelerator 10. Then, fuse 11 was lowered into the well on a detonating cord, which was also filled with explosives until it was completely covered. When the accelerators were installed, their cones were turned towards the fuse.

In general, for 72 exploding wells, the consumption of accelerators was 3-4 cavities per 1 well, with the upper location of the fuse, electric detonation was carried out in an orderly manner. According to the results of explosive stripping, the average size of the pieces of the chipped rock mass was mainly 90-120 mm, and the maximum diameter of the pieces was 320-450 mm (Figure 9). At the same time, as can be seen from Figure 8, with a decrease in the diameter of the well from 250 to 150 mm, the diameter of the average piece of destroyed rock mass decreased from 170-190 to 90-120 mm.

The analysis of high-speed photography data obtained in laboratory studies, as well as the results of pilot tests, in authors' opinion, confirm the previously suggested assumptions that the use of volumetric cavities (accelerators) in the explosive charge focusing the cumulative flow on the destructible medium, increases the rate of detonation of the charge and, accordingly, creates an increased pulse of the explosive

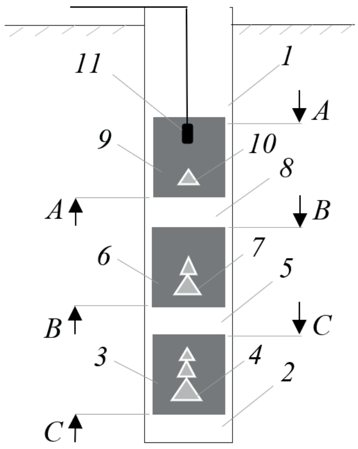

Figure 8 *Formation in a well: 1 - well, 3, 6, 9 - portions of explosives, 4, 7, 10 - accelerators, 2, 5, 8 - air barriers, 11 - fuse on a detonating cord*

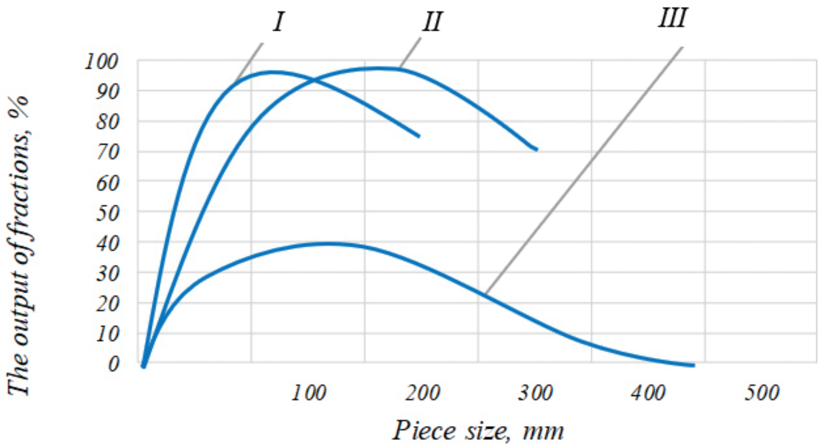

Figure 9 *Dependence of the average piece during the downhole drilling on the diameter of the well: I - 150 mm, II - 250 mm and III - the distribution of the lumpiness of the blasted rock mass*

wave, which, in the end, makes it possible to improve the quality of crushing of the test sample (rock mass).

To confirm the results obtained by the authors, the pilot experimental explosions were carried out in 2016-2019 at a number of mining facilities in Kazakhstan. At the Sarbaisky iron ore quarry of JSC "Sokolovsko-Sarbaisko Concentrating Production Association" (JSC "SSGPO", Rudnyy) at the height of the ledge of 27 m, the wells were mainly drilled 30 m deep with a re-drill of 3 m, and the delivery of explosively prepared rock mass from a considerable depth to the surface of the quarry was carried out by dump trucks of large load capacity. The cyclical nature of the technological process of transportation of rock mass using road transport, which takes considerable time to lift the ore to the surface, leads to a decrease in mining productivity.

In 2016, for experimental purposes, 10 tons of explosives were detonated at the Sarbaisky open pit using developed accelerator designs in 18 boreholes 250 mm in diameter and 23 m deep. In 2019 at the same quarry, 50 tons of explosives were detonated in 70 boreholes and almost 1,000,000 m^3 of rock mass with expected lumpiness (400-450 mm) and absence of oversize was prepared by blasting. According to the test results, the production specialists noted that the proposed drilling and blasting technology of mineral extraction promotes wider application at the open pits of SSGPO JSC of the means of transportation providing continuous delivery of ore from the bottom of the pit to the surface: conveyors, pneumatic or hydraulic transport. It was also noted that the results obtained from pilot tests, in general, reflected the correlation dependence between the parameters of explosive stripping and the design values of the hole, presented in Equation (20).

Experimental explosions with the proposed accelerator design were also conducted in conditions of underground mining, in particular, at the mine "Kvartsitka" of JSC "Altynalmas" (Stepnogorsk), developing gold-bearing ores. Total of 28 boreholes were drilled through the viscous quartzites. With the length of the borehole up to 3 m and the number of cartridges in one borehole equal to 6, each cartridge was filled with one volume cavity. Experimental explosions during the drifting, along with a significant crushing of rock mass, also showed an increase in the borehole utilization factor to 0.94, with the existing normative value of 0.84, Figure 10.

5 Analysis of the results obtained

As is known, the basic information about the detonation process of condensed media is provided by experiment, and the criterion for the successful application of the hydrodynamic theory should be the compliance of the detonation parameters obtained experimentally with the theoretical results [29]. In this regard, the results of laboratory and pilot tests for conducting explosive stripping using volumetric cumulative cavities (accelerators) allowed us to propose the following physical model of the processes occurring during the explosion of a borehole explosive charge. During the explosion of the borehole charge shown in Figure 8, the detonation products, spreading from the fuse 11, pass through the single-cone accelerator 10 and assemble into a single cumulative flow, the speed of which is higher than the detonation velocity of explosive substance 9 to the accelerator. Such a flow has high kinetic energy and, getting into the elongated redistributive part of the accelerator 10, changes the direction of its propagation perpendicular to the surface of the concave accelerator generatrix.

The cumulative flow, while simultaneously exciting the explosion of the explosive charge located around the accelerator, increases the mass of explosives exploding per unit of time. Considering that the generatrix of the redistributive part of the accelerator 10 has an inward concavity, the voltage waves are focused outside the charge at points F (Figure 11, a).

The explosion products, approaching the air partition 8, reduce their speed, but on the way to the middle part of the charge they acquire the detonation rate of the explosive substance charge 6. When the explosion products pass through the accelerator 7 (Figure 8), they gather into an amplified two-fold cumulative flow, the speed of which is higher than the flow rate after the accelerator 10.

This enhanced cumulative flow penetrates the void of the twin accelerator 7 and explodes the explosive charge 6, directing the explosion products perpendicular to the surface of the accelerator 7, and given that its surface is concave inward, voltage waves focus at points F outside the charge (Figure 11, b). Further, the explosion products, approaching the air partition 5, reduce its speed, but when the explosive substance 3 charge is excited in its lower part, it again acquires the detonation velocity

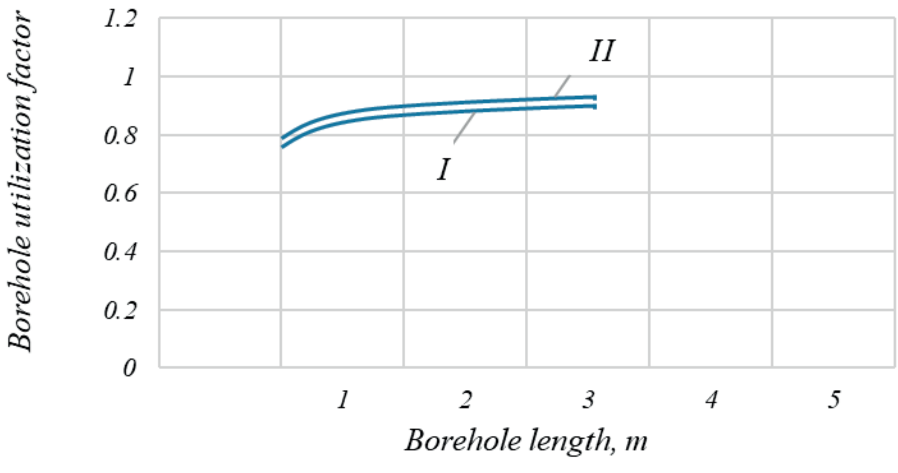

Figure 10 *Values of the borehole utilization factor during the borehole coring: I - without the use of volume cavities, II - with the use of accelerators*

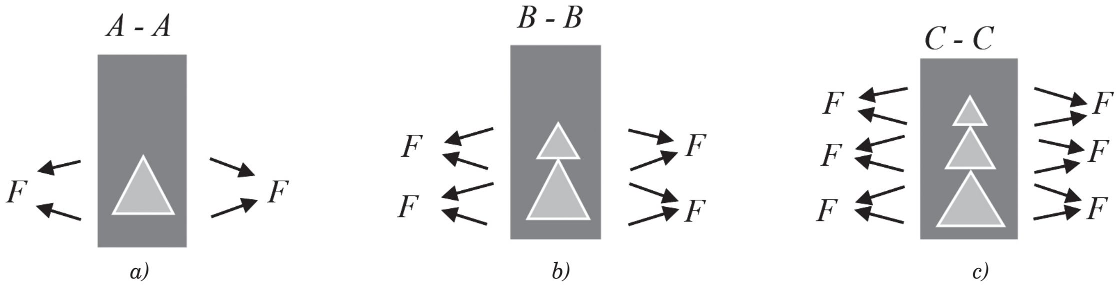

Figure 11 *Sections of the down hole explosive charge, shown in Figure 7, with one-, two- and three-cone accelerators*

of explosive substance 3. When the explosion products pass through the accelerator 4 (Figure 8), they gather again into a more amplified three-fold cumulative flow, the speed of which is higher than the flow rate after the accelerator 7. The three-fold amplified cumulative flow penetrates the void of the accelerator 4, explodes a large mass of explosive substance 3 charge around the elongated accelerator and focuses voltage waves outside the charge in the destructible array at points F (Figure 11, c). In other words, accelerators in charges, firstly, accelerate the speed of explosion products, and secondly, provide dynamic braking of explosive gases, which ensures the explosion of a larger mass of explosive charge and the reversal of the explosive pulse by 90 degrees.

6 Conclusions

Based on the results of modelling the process of explosive stripping in laboratory conditions and conducted pilot tests at a number of mining sites in Kazakhstan a method is proposed for the controlled explosive stripping of rock mass with the use of developed designs of volumetric cavities (accelerators). Due to the use of accelerators in the borehole explosive charge dynamic braking of explosion products is carried out, contributing to the emergence of localized destruction due to tensile and bending forces acting on the destroyed massif.

As a result, the specified mode of crushing of the crushed rock mass is provided (maximum lump size according to the results of tests in the conditions of mining enterprises does not exceed 450 mm), which, according to the estimation of production specialists, contributes to the possibility of wider application of flow transport means at open pits: conveyors, pneumatic and hydraulic transport.

In addition, the results of the conducted pilot tests in conditions of open-pit and underground mining showed the possibility of:

- reduction of explosive charge mass in a borehole by 32-36% in comparison to the approved passport of drilling and blasting operations by means of arrangement of air gaps in boreholes;
- reduction of drilling costs by 24-28% due to the transition to a smaller borehole diameter;
- increasing the borehole utilization factor up to 0.94.

The results of preliminary design study of implementation of the proposed technology of drilling and blasting operations and the effectiveness of cyclic-flow technology, using the belt conveyors at the Molodezhny open pit mine (Karaganda region, Republic of Kazakhstan), showed an increase in mining productivity up to 5 million tons, reducing development costs by 25-30%, and, accordingly, the possibility of effective development of deeper horizons.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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