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Improvement of blasting technology at gold-ore mining enterprises using contour blasting

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Abstract

Purpose. The research purpose is to develop and substantiate recommendations for improving the technology of drilling-blasting operations in open-pit mining of gold-ore deposits. The research is aimed at optimizing the drilling-blasting process parameters taking into account physical-mechanical properties of rocks, conditions of ore mass occurrence and requirements for the quality of rock mass crushing.

Methods. Qualitative and quantitative analysis methods are used for the research. The compliance of the drilling-blasting technology with the design solutions is assessed, and the actual condition of the quarry benches and near-wall mass after blasting is analyzed. A numerical model describing the influence of contour blasthole charges on the near-wall mass has been developed, taking into account the parameters of the bench height and charge diameter. Particular attention is paid to the development of recommendations for improving the quality of ore mass breaking, decreasing dilution and reducing the near-wall mass breaking. The effectiveness of the proposed solutions is confirmed by conducting a series of test blasts with subsequent assessment of their results.

Findings. The research results have shown that the existing parameters of drilling-blasting operations at the Pustynnoye Mine do not fully comply with the mining-technical conditions, which leads to inconsistency with the design slope angles and dilution of rock mass. Implementation of the presplitting method and optimization of charge parameters make it possible to improve the quality of mass breaking and reduce the seismic impact. The resulting dependences will help to accurately select blast parameters, improving the efficiency of drilling-blasting operations.

Originality. The novelty is in the development and implementation of an integrated approach to the optimization of drilling-blasting operations at the Pustynnoye Mine. The research has identified the optimal parameters, including blasthole diameters, charges for splitting, explosive density and stemming material granulometric composition.

Practical implications. Implementation of the proposed methods will increase the efficiency of drilling-blasting operations, improve rock mass crushing, stabilize slopes and reduce seismic impact on the near-wall mass. Optimizing parameters such as blasthole diameters, specific explosive consumption and charge densities will reduce costs while maintaining efficiency. The developed passports of drilling-blasting operations will help to adapt the processes to changing conditions and ensure the safety and accuracy of mineral extraction.

Keywords: *mining, quarry, bench, blasting operations, slope stability, crushing, rock mass, blast energy, failure zones*

1. Introduction

Mining of precious metals in Kazakhstan plays a key role in the development of the national economy. Significant reserves of gold and other precious metals make their development a priority for the mining industry. Kazakhstan is the leading gold producer in Central Asia, and the gold mining industry is a strategically important sector contributing to the inflow of investments and strengthening the country's export potential [1]-[3].

According to the data of the Republican Agency for Statistics, in recent years there has been a steady growth in gold mining volumes, which, last year, amounted to 40-50%. This growth is due not only to increased global demand and high gold prices, but also to the active development of previously unprofitable deposits with complex mining-geological conditions [4], [5]. Modern mining requires detailed planning to reduce ore losses and ensure selective extraction, especially under complex structural and hydrostatic conditions [6], [7].

The largest companies providing the development of the industry include such enterprises as JSC AK Altynalmas, KAZ Minerals LLP, Polymetal Eurasia JSC and others. These companies are implementing advanced exploration and mining methods, including leaching technology, underground mining and the use of digital solutions for process control. Recent research also highlights the use of machine learning techniques to optimize material behavior prediction and resource processing in mining-related industries [8].

Given the growing scale of open-pit mining and the complexity of maintaining slope stability, recent research emphasizes the need for advanced geomechanical monitoring and

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land-use planning to ensure operational safety and long-term environmental resilience [10]-[15].

Currently, one of the priority directions for scientific research and production activities is optimization of drilling-blasting technologies. The main focus is on developing methods aimed at minimizing ore loss and dilution, as well as at improving the stability of rock masses. Such approaches are of particular importance for fields mined by open-pit mining in difficult mining-geological conditions, where traditional methods are often insufficiently effective [16]-[18].

When mining gold-ore deposits using open-pit method, the key importance is given to the parameters of drilling-blasting operations that ensure compliance with the design characteristics of benches, including slope angles, as well as maintaining the near-wall mass continuity when exposed to seismic waves caused by blasts. In this paper, the authors study the issues of improving the technology of drilling-blasting operations on the example of Pustynnoye gold-ore field, mined by the mine of the same name, belonging to JSC AK Altynalmas.

Based on the results of previous studies, it has been found that when mining the Pustynnoye field, there are significant difficulties in performing drilling-blasting operations in 10 m high benches characterized by the presence of developed fracturing and large cavities [19], [20]. These peculiarities of rocks contribute to the natural separation of the mass into large fragments, which complicates breaking.

Additionally, when using the simplest explosives based on ammonium nitrate, there is a significant release of gases (up to 900 l/kg), which contributes to an additional mass splitting. Filling the fractures with explosion gases increases the stress in the rock mass up to 1.5 times, which complicates the fulfillment of design requirements along the contour of the stope extraction and leads to increased losses of ore and impurities at the ore-rock boundary. This, in turn, reduces the quality of the extracted mineral by 20-25%.

The Pustynnoye gold-ore field is located in the Karaganda region and serves as a raw material base for the Pustynnoye mining-metallurgical complex, which is part of JSC AK Altynalmas. Seven ore bodies have been identified within the ore zones of the field. The commercial ore bodies are limited to 0.5 g/t cut-off grade of gold. The boundaries of these ore bodies are indistinct and can only be accurately defined based on sampling results. Ore bodies are sheet-like and lens-shaped deposits, which vary in thickness from a few meters to 112 m. The deposits are characterized by a steep dip with an inclination angle from 60 to 90°, with twitches and swells, extending submeridionally within the range of 315-320° [21], [22]. The main morphological parameters of ore bodies are given in Table 1.

Table 1. Main morphological parameters of the Pustynnoye field ore bodies

No. of exploration lines	Traced to the dip, m	Traced along the strike, m	Thickness, m from-to / average	Dip angle, deg from-to	Azimuth of strike, deg	Gold content, g/ton from-to / average	Gold reserves, % of total
Ore body 1							
1-12	300	440	3-112 / 41	45-90	340-0	0.5-6.57 / 1.49	67.1
Ore body 1a							
8-12	285	208	2.5-37 / 7.2	66-90	315-335	0.53-2.14 / 1.38	4.1
Ore body 1b							
8-12	259	188.5	2.5-27 / 6.9	78-90	330-20	0.5-2.03 / 1.46	2.2
Ore body 2							
3-8	110	218.5	2.0-20 / 6.4	60-83	300-315	0.55-4.8 / 1.09	1.5
Ore body 2a							
10-13	214	173.5	1.5-72 / 15.2	70-90	330-315	0.63-2.9 / 1.23	5.7
Ore body 3							
9-11	210	120	10-100 / 54.4	68-90	–	0.5-3.04 / 2.08	18.4
10	20	50	8-18 / 7.3	–	–	4.46	1.0

The physical-mechanical properties of the rocks of the field vary depending on their lithological type, mineral composition, and depth of occurrence, varying within the following limits:

– bulk density ranges from 2.63 g/cm³ (serpentinite) to 2.82 g/cm³ (pilite);

– specific density ranges from 2.51 g/cm³ (serpentinite) to 2.80 g/cm³ (pilite);

– porosity varies from 0.4% (pilite, siltstone, andesite) to 6.6% (carboniferous sandstone);

– compressive strength ranges from 72.9 MPa (carbonaceous siltstone) to 275.0 MPa (sandstone), and tensile strength ranges from 7.0 MPa (carbonaceous siltstone) to 26.25 MPa (sandstone).

Similar geological heterogeneity, including the presence of complex lithologies and ophiolitic structures, has been documented in adjacent regions of Central Asia and the Afghan Central Block [23]-[25].

Currently, the field is being mined by open-pit method, with stoping operations at 10 and 5 m high benches. According to the design solutions, the slope angle of the benches is 60° in the diorite zone and 70° in the primary rock zone.

The ore and the host rocks are broken using a drilling-blasting method. The blastholes are 165 and 251 mm in diameter. ANFO explosive is used to break the rock mass, and in areas with higher rock density, Fortis Extra high-density explosive with a density of 1.25 g/cm³ is used. Blasting operations are performed using i-kon electronic initiation systems and non-electric blasting systems. For double detonators, the deceleration is provided: 500 ms in the blasthole and 25, 33, 42, 65, 89, 130 ms on the surface. Specialized Orica Company conducts all operations related to drilling-blasting operations.

Previous studies have shown that unstable results of rock crushing were observed when breaking 10 m high benches at the Pustynnoye Mine using 200 mm diameter blastholes, 2.5 m long stemming and specific explosive consumption in the range of 0.55-0.75 g/cm³. The broken ore was characterized by high hardness and abrasiveness, which created additional difficulties in processing and transportation.

In modern conditions, the impossibility of ensuring the design slope angles of the benches has been added to the existing problems of drilling-blasting operations at the mine. The main reasons for the formation of gentle slope angles are the breaking of the upper edge and insufficient mining of the lower edge. These phenomena are caused by the use of standard blasting methods with vertical blastholes, the use of high-energy explosives close to the quarry wall, incorrect selection of the lower edge displacement distance, irrational distribution of blast energy and excessive localization of blast energy. The analysis has shown that drilling-blasting projects do not always take into account changing technological conditions caused by variations in the structural characteristics of the ore and host mass.

According to the Hoek-Brown criterion [26], at a bench height of 10 m, an uncontrolled or inadequately controlled blast can cause significant damage to rocks at a distance of 20-25 m outside the blast contour. The use of blasting process control technologies makes it possible to reduce the area of breaking to 3-12 m. The main purpose of near-wall blasting in quarries is to maintain the stability of slopes. According to studies [27]-[29], the depth of rock breaking in the blast zone depends significantly on the height of the bench. The breaking process is accompanied by changes in the rock structure, a decrease in its strength characteristics, changes in elasticity moduli, as well as the formation and opening of new fractures.

The planning of drilling-blasting operations, aimed at minimizing negative impacts on slopes, requires consideration of mechanical failure mechanisms, including vibration processes that provoke the formation of new fractures, the impact of explosive gases that contribute to the opening of existing fractures, as well as forces influencing the quarry slopes and determining the nature of their breaking, which influences the redistribution of loads [30], [31].

The development of drilling and blasting technologies, including the optimization of charge structure, initiation techniques, and energy distribution, has received considerable attention in recent studies [32]-[35]. In particular, advanced initiation methods such as sectional and wave-based techniques are being explored for enhanced control of rock fragmentation [36]-[39]. Considering the environmental impact of large-scale extraction, researchers are increasingly focusing on waste utilization, risk mitigation, and reclamation of disturbed lands [40]-[42]. These approaches align with modern sustainability principles in mining.

The analysis conducted made it possible to identify key areas for improving drilling-blasting technology at the Pustynnoye Mine. These include: the use of smaller diameter blastholes, introducing contour blasting with the preliminary formation of splitting zones, conducting contour blasting in narrow rows, and limiting the blast energy exposure area. In this regard, our research is aimed at analyzing the existing technology of drilling-blasting operations and their parameters, as well as at developing recommendations for their further optimization.

2. Methods

It is known that when a single blasthole charge is detonated, the blast energy at the initial moment of time propagates uniformly in all directions, transferring a significant impulse to the environment. The high-stress shock wave maintains its impact within the crushing and fracturing zones where the rock experiences the most intense breaking. Outside these zones, however, the wave stress intensity decreases significantly, reaching values that do not exceed the compressive strength of the rock. Additionally, the pressure of the blast products decreases rapidly due to spatial energy dissipation and penetration into existing fracture systems. In cases where there is an exposed surface within the third zone, the blast products concentrate their effect on this surface. This results in a rock breaking directed deep into the mass, accompanied by the opening and increase in fracturing of the mass.

Studies have shown that the shape of the breaking zone in the plane perpendicular to the charge axis varies from a half-ellipse to a half-circle, which is determined by the position of the blastholes relative to the exposed surface of the mass. Furthermore, taking into account the constancy of the breaking zone radius for the blasthole charge in the given mining-geological conditions, it is possible to find the optimal location of blastholes.

Obviously, the most effective position of the charge is the one that maximizes the breaking zone area in the plane perpendicular to the charge axis. The Least Resistance Line (LRL) value of the bench, providing the maximum destructive efficiency of the explosive charge and the design slope angles of the benches, can be considered as optimal for the Pustynnoye field quarry.

When detonating a single explosive charge at the optimal LRL value (W_0), a stress state is formed in the area of the bench edge, caused by the propagation of the shock wave and the impact of detonation products:

$$\sigma_0 = \frac{7.5 Q_0 \Delta d H}{W_o^2}, \text{ MPa}, \qquad (1)$$

where:

Q_0 – the specific heat of blast, kcal/kg;

Δ – a charge density, kg/m^3;

d – the blasthole diameter, m;

H – the bench height, m.

If the LRL of the bench increases relative to the optimal value (W_0), the stress at the point of the bench edge will decrease. This is due to the decreased blast energy concentration, as the shock wave attenuates as the distance from the charge increases, and the detonation products dissipate in the rock mass:

$$\sigma_f = \frac{7.5 Q_0 \Delta d H}{W_f^2}, \text{ MPa}. \qquad (2)$$

In this case, the following is true: $\sigma_f < \sigma_0$, which means a decrease in the stress on the bench edge line (σ_f) relative to the maximum value (σ_0) at the optimal LRL (W_0). An increase in the least resistance line of the bench ($W_f > W_0$) causes the stress generated by the blast at that point to be lower than under optimal conditions.

In order to form a breaking zone with a profile corresponding to optimal blasthole placement, it is necessary to fulfill the following condition: $\sigma_0 = \sigma_f$.

To achieve equality of these stresses, the stress σ_f must increase by a value of k, where k is the difference between the current stress σ_f and the optimal stress σ_0.

Then: $\frac{7.5 Q_0 \Delta dH}{W_o^2} = \frac{7.5 Q_0 \Delta dH}{W_f^2} \cdot k$, hence $k = \frac{W_f^2}{W_0^2}$.

On the other hand, if to take into account the distribution of stresses arising from adjacent charges on the bench, which characterize the rock state at the point opposite to the blasting blastholes when a series of charges detonates, then it becomes possible to determine the parameters of the distribution of blast energy and stresses in the mass:

$$\sigma_a = \sigma_f \frac{3W_f^2 - a^2}{W_f^2 + a^2}, \text{ MPa}, \tag{3}$$

where:

a – the distance between charges, m.

Then, solving Equation (3) with respect to parameters W_0, W_f and a, it is possible to obtain the expressions:

$$3W_f^2 \cdot W_0^2 - a^2 W_0^2 = W_f^4 + W_f^2 a^2;$$

$$3W_f^2 \cdot W_0^2 - W_f^4 = a^2 W_0^2 + a^2 W_f^2;$$

$$W_f^2 \left(3W_0^2 - W_f^2\right) = a^2 \left(W_0^2 + W_f^2\right).$$

Then the distance between the blastholes can be determined as follows:

$$a^2 = W_f^2 \frac{3W_0^2 - W_f^2}{W_0^2 + W_f^2}, \text{ m or } a = W_f \sqrt{\frac{3W_0^2 - W_f^2}{W_0^2 + W_f^2}}, \text{ m}. \tag{4}$$

When a charge is detonated, a compression wave is generated in the rock medium and propagates from the blast point to the exposed surface. Zones with different stress levels are formed around the charge. As the distance from the charge increases, the compression wave intensity decreases, which is due to the geometric dissipation of the blast energy, as well as due to the energy spent on the movement and breaking of the mass in the nearest zone from the point of blasting. As a result, stresses are reduced in zones more distant from the charge, and the blast energy is distributed over a wider area, resulting in a weakening of the breaking effect.

According to the data of a number of studies [43]-[45] and the results obtained by the authors when creating a numerical model for blasting the blasthole charges on benches using the integrated ANSYS program, a stress distribution zone is formed in the sectional plane along the charge axis, taking the form of ellipses. Thus, when the charge detonates in the rock medium, stress zones are created around it, which in their geometric shape correspond to ellipsoids of rotation.

Based on the selected rock breaking mechanism, if a stress wave with an intensity reaching the ultimate tensile strength of the rock reaches an exposed surface, then spall formation occurs on this surface [46], [47].

The sizes of the torn-off pieces depend on the value of stresses acting in the rock and can be determined by the following expression:

$$e = \frac{l \cdot \sigma_t}{\sigma_r}, \text{ cm}, \tag{5}$$

where:

e – the size of the resulting piece, cm;

l – the length (thickness) of the zone for which the piece size is determined, cm;

σ_t – temporary rock tensile strength, MPa;

σ_r – the stress value in the zone for which the piece is measured, MPa.

Thus, the main approach to the study of the nature of the rock mass crushing is the analytical method, which allows modeling the zones with a given degree of rock crushing. To improve the reliability of the results, this method is supplemented by a comparison with data from production blasts. In addition, a qualitative and quantitative analysis of the existing drilling-blasting technologies, their compliance with the design parameters, as well as assessment of the actual condition of the quarry benches and near-wall mass after blasting is performed. Based on the obtained data, recommendations are developed for improving the quality of ore mass breaking and reducing the degree of near-wall mass disturbance with their subsequent verification during test blasts.

3. Results and discussion

In accordance with the above methodology, for the conditions of the Pustynnoye field, the distances are calculated between blastholes of the first row, as well as the second and subsequent rows, including distances between rows. Calculations are made with regard to the categories of rocks by blastability coefficient for the 10 m high bench (Table 2).

Table 2. Calculation of distances between blastholes and rows for a 10 m high bench taking into account the categories of rocks by blastability coefficient (Pustynnoye field)

Categories of rocks by blastability coefficient	Subdrill, m	Optimal LRL value, m		Distance between blastholes in the first row, m		Distance between the rows of blastholes, m		Distance between blastholes for the second and subsequent rows, m	
		Charge diameter, mm		Charge diameter, mm		Charge diameter, mm		Charge diameter, mm	
		165	216	165	216	165	216	165	216
Easy-to-explode	0.7-0.8	7.0	7.6	6.8	7.6	5.1	6.5	5.1	6.5
Moderate-to-explode	0.8-1.0	6.5	7.2	6.3	7.1	4.7	6.2	4.7	6.2
Hard-to-explode	1.1-1.2	6.0	7.0	5.5	6.9	4.2	6.6	4.2	6.0

One of the key parameters determining the efficiency of drilling-blasting operations is the distance between blastholes drilled both within the same row and between rows. This parameter has a direct influence on the quality of rock crushing, formation of design angles of bench slopes and reduction of the near-wall mass breaking. It is particularly important to correctly determine the distances between the lower and upper ends of the contour blastholes and the project wall, which depends on the charge diameter and geomechanical characteristics of the mass. Given these interrelationships, this factor has been chosen as the main criterion in checking the correctness of the calculation method used to calculate the parameters of drilling-blasting operations, which allows for their optimal organization and maximum productivity.

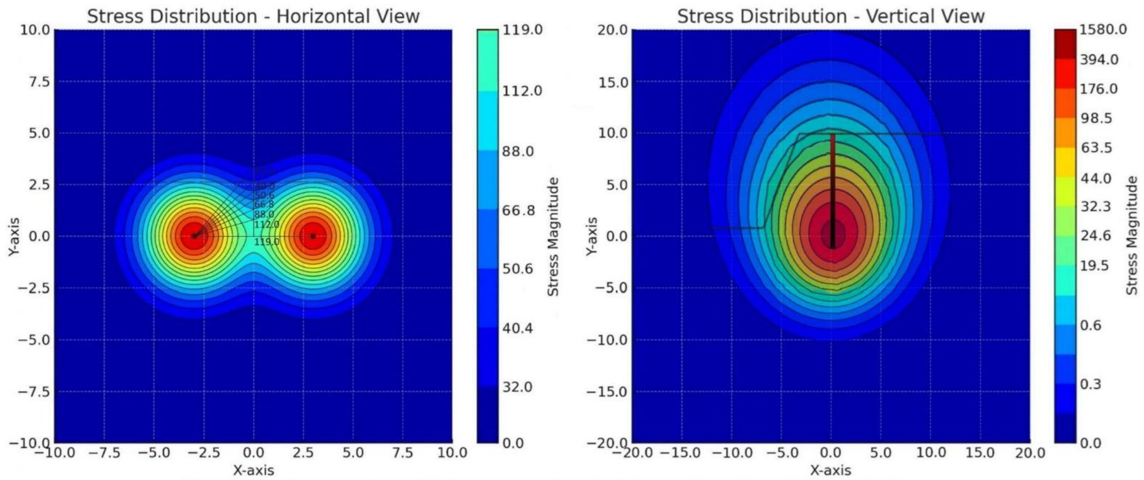
In addition, we can note that the analytical method is the main approach to the study of the nature of rock mass crushing. This approach allows the modeling of zones with a specified degree of rock crushing, which contributes to a more accurate assessment of the efficiency of drilling-blasting operations and optimization of their parameters.

It is known that the main zones of formation of oversized fractions on the bench are the bottom edge and the area of the bench located above the charge. Control of the blasting process, aimed at achieving a high degree of rock mass crushing, is determined not only by the properties of the blasted medium, the type and size of the explosive charge, but also by the design of the charge and a number of other factors.

The study of charge design as a key factor that increases the useful work of the blast and reduces the proportion of coarse fractions of the blasted rock is conducted using modeling of the stress distribution around the detonated explosive charge. Based on the results obtained, the patterns of rock lumpiness distribution along the bench height in the breaking zone are analyzed, and these data are compared with the results of production blasts.

When using a solid column charge, the largest amount of oversized material is formed in the area adjacent to the end part of the charge. This is due to reduced blast wave intensity in the end zone and insufficient energy reaching the upper part of the bench to crush the material effectively.

A numerical model of the bench has been developed using the ANSYS software package to analyze the impact of a contour blasthole charge blast on the near-wall mass. The model takes into account the parameters of a 10 m high bench and 165 mm diameter charges. In the process of modeling, stress distributions in the mass are analyzed, corresponding to theoretical ideas about breaking zones occurring at different distances from the charge chamber (Fig. 1).



Points	1	2	3	4	5	6	7	8	9
α, deg	66	45	35	25	23	19	17		
MPa	119.0	112.0	88.0	66.8	50.6	40.0	32.0		
MPa	1580.0	394.0	176.0	98.5	63.5	44.0	32.3	24.6	19.5

Figure 1. Stress distribution in the rock mass during blasting of blasthole charges on a bench

Within the specified zones, the sizes of fragments formed as a result of mass breaking are determined. Based on the modeling results, the granulometric composition of the blasted rock mass is calculated (Table 3).

Table 3. Calculated granulometric composition of the blasted rock mass depending on the distance from the charge chamber

Piece size, cm	Granulometric composition of blasted rock mass, %
up to 20	27.5
21-40	21.9
41-60	27.5
61-80	13.2
81-100	9.1
over 100	1.8

Figure 1 analysis shows that when using charges with fixed length and constant diameter, the character of stress distribution in the mass does not change with increasing LRL. However, the shape and sizes of breaking zones depend on the LRL value: the minimum sizes are characteristic of elliptical-shaped zones, which increase as the exposed surface approaches the charge, reach a certain maximum, and then decrease.

The change in the sizes of breaking zones has a direct influence on rock crushing efficiency. A significant distance of the exposed surface from the charge results in an increase in the sizes of the broken pieces, while the proximity of the surface contributes to uniform crushing and the formation of the design slope angles of the benches. Under conditions of multi-row blasting, optimal positioning of blastholes of the second and subsequent rows relative to each other improves the crushing quality. At the same time, the use of contour blastholes with reduced-diameter charges relative to the main ones is reasonable.

Thus, the LRL value of the bench plays a key role in controlling the crushing process during blasting of blasthole charges. Optimal blasthole placement, taking into account the mass resistance, allows achieving the maximum volume of blasted rock, minimizing the yield of coarse-block fractions and ensuring the design slope angle of the bench.

According to the above parameters and methodology, four test blasts are conducted in the quarry of the Pustynnoye field on the upper benches located in the northern part of the quarry, with modified parameters for drilling-blasting operations (Fig. 2). The total data from these blasts are presented in Table 4.

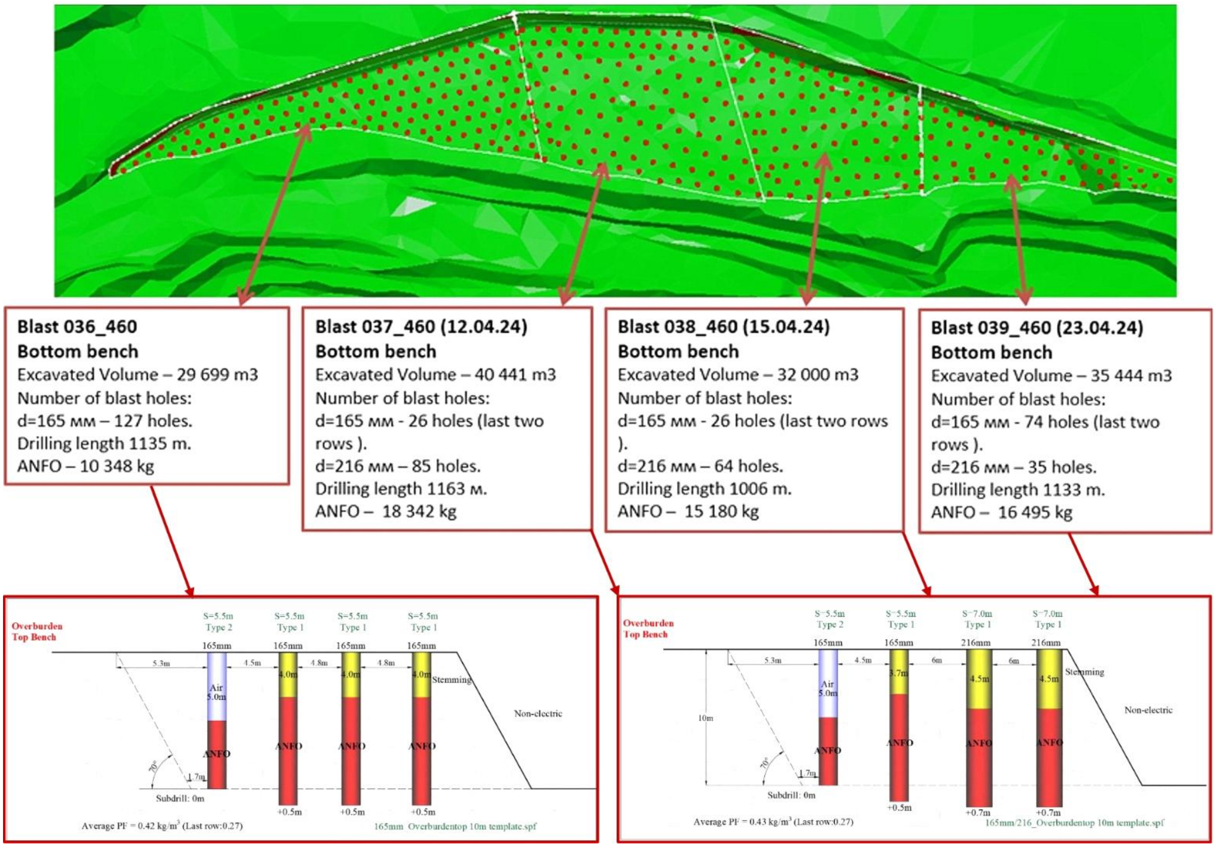


Figure 2. ayout of blasthole charges and parameters of test blasts on the block 460 upper benches of Pustynnoye field quarry

Table 4. Results of test blasts on the block 460 upper benches of Pustynnoye field quarry

No. of test blasts	Distance from the bottom edge of the bench to the contour blastholes, m	Indicator of the state of the bench top edge	Change in height of the bench top edge, m	Change in the bench bottom edge, m	Average wall angle, deg
460-036	2.0	There is a loss	No	1.5-2.0	55
460-037	2.2-2.8	No loss	< 1 m (minor)	1.0	64
460-038	1.4-1.7	Loss – 1 m	< 1 m (minor)	1.3	60
460-039	1.0-1.6	There is a loss (minor)	1-2 m (minor)	1.5	67

Analysis of the performed test blasts has revealed several important factors influencing the blast energy distribution efficiency. In particular, inefficient energy distribution was observed with 165 and 216 mm diameter blastholes (blast 460-038). Moreover, the rows of blastholes did not coincide with the design line of the top edge (blast 460-038). In the case of blast block 460-037, there was an underdrilling in the last two rows of blastholes on the upper bench of the 475 m mark, which resulted in an increase in the lower edge above the 460 m mark. This was due to the fact that the blastholes were located at a level of about 463 m, and the distance from the bottom edge to the contour blastholes in the last row was 2.5-2.8 m.

For blast 460-036, it was recorded that the distance from the bottom edge to the contour blastholes was found to be too large, which is due to the increased strength of the rock than initially assumed.

Qualitative analysis of the broken rock mass indicates the presence of primary rock that is mixed with surface rock as a result of the blast, which is typical for blasts 460-038 and 460-039, as shown in Figure 3.

The results of the test blasts demonstrate that presplitting using a high-energy explosive can be effectively used in areas with surficial and oxidized rock. This approach is significantly more cost-effective than using continuous split-forming charges. However, the use of a high-energy explosive for presplitting is not reasonable in oxidized hard rock conditions, since the improvement of crushing quality in these zones is significantly limited.

When using 165 mm diameter blastholes, a hole collar spacing of about 2.2 m is optimal. Under such conditions, it is preferable to use ANFO explosives in water-free blastholes and Fortis charges with a density of 1.15 g/cm³ in watered blastholes.

Figure 3. Mixing of primary rocks with surface rocks as a result of blasting

This method is suitable for both single and double benches with 0.5 m subdrill. It is recommended to use a 10 g detonating cord inside the blasthole and a 5 g detonating cord on the surface as detonating means.

The analysis of data obtained during test blasts and experience of gold mining enterprises both in our country and abroad testifies to a high level of efficiency of using continuous split-forming cartridges with diameter of 26 or 32 mm on intermediate and final walls, as well as on double benches with subdrill of blastholes by 0.5 m, while the upper 2 m of blastholes remain uncharged.

Under the existing drilling-blasting technology at the Pustynnoye field, there is a significant impact of the shock wave on the intermediate walls of the quarry. This leads to the formation of new fractures, resulting in only about 50% of the benches satisfying the design requirements of slope angles (60° or more). This discrepancy threatens the project discounted cash flow, which could be reduced by between \$51 million and \$92 million unless the slope angle of the bench is increased to accommodate the parameters of the future intermediate and final quarry walls. This requires the use of special quarry control methods.

One of the most effective methods is the widespread use of contour blasting with presplitting, which requires reducing the blasthole diameter to 165 mm. In addition, contour blasts can be developed using free face surface, but this method has the significant disadvantage – the impact on quarry productivity.

In order to increase the efficiency of blasting and to ensure the preservation of the out-contour mass by increasing the slope angle of the bench, while improving the granulometric composition of the broken ore and the use of explosive energy, at the Pustynnoye Mine, it is recommended to use the contour blast method, in which single or continuous charges from priming cartridges with 0.18-0.2 diameter of the blastholes with explosive density of 1.2 g/cm³ are placed in the pre-contour blastholes with a diameter of 165 mm. They are detonated with a deceleration of no more than 500 ms. This technology preserves the out-contour bench space, increases the slope angle of the bench and improves the crushing quality of the broken ore. The energy flows generated when blasting explosive charges are directed to the surface of the split, partially passing into the out-contour part of the rock mass, which reduces the amount of energy passed and increases the amount of reflected energy. In this case, the distance between hole collars should be 1.8 m at a specific consumption of explosive of 0.50 kg/m³ for moderate-to-explode rocks and 1.5 m at a specific consumption of explosive of 0.60 kg/m³ for hard-to-explode rocks, such as sandstone.

For more efficient distribution of the blast energy to the base of the bench, the charge value along height is 65-70%, while the charge density increases to 1.2 g/cm³. The remaining part of the blasthole is filled with fine rock fractions. The consumption of explosives per blasthole remains unchanged, and charge compaction occurs by reducing its value in height.

Figure 4 shows an example of a continuous presplitting product from priming cartridges, containing a 10 m detonating cord used for effective rock breaking during drilling-blasting operation. Combined blasts, which include both contour blasting and conventional blasting with vertical blastholes, can be particularly effective. These blasts have to be initiated in a different way (Fig. 5).

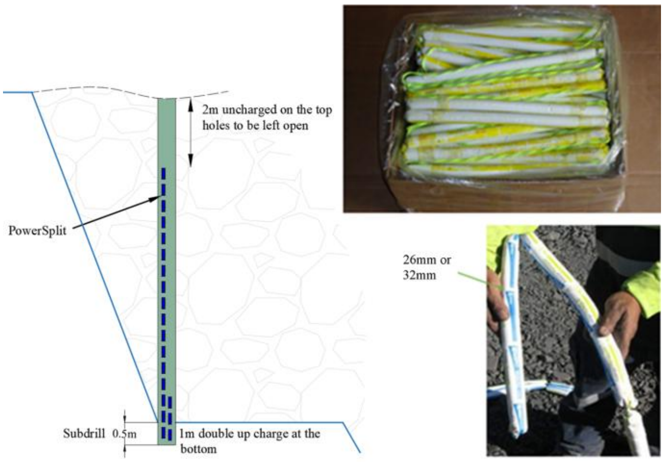


Figure 4. Example of a continuous split-forming product with a 10-m detonating cord

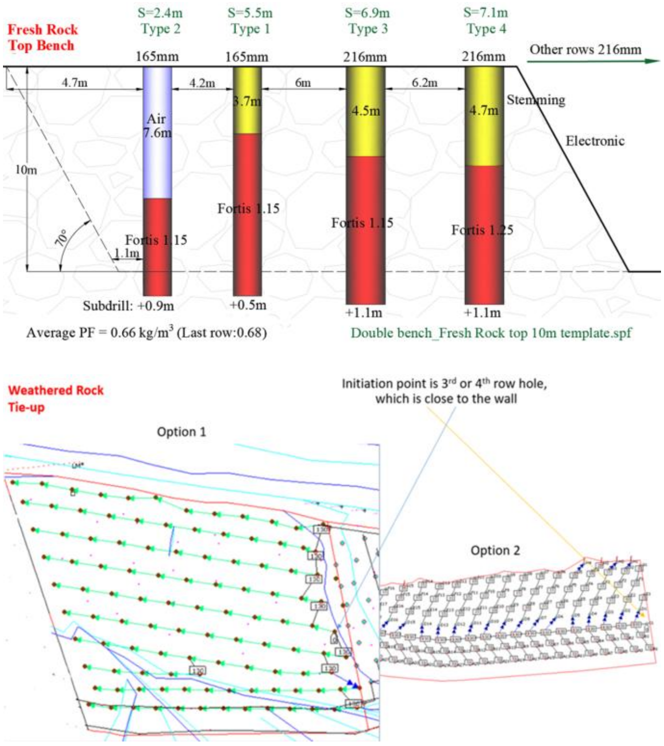


Figure 5. Near-wall blast projects using contour blasting: (a) blasthole charging scheme for fresh rock; (b) options for schemes for linking blasts in the weathered rock zone

In this situation, 2-3 rows of 165 mm diameter buffer blastholes located behind the blast zone are used. These rows are loaded with regard to the differences in technology compared to operating blastholes. The electronic initiation system is used to initiate with time intervals similar to those used in other types of connections. Initiation is done from the wall side of the quarry. For the last group of 3-4 rows of blastholes, an initiation interval of 4 milliseconds is set. The last three rows should have an interval of 30-40 ms/m, while the remaining rows should have an interval of 20-25 ms/m, which corresponds to the optimal technology of conducting blasting operations.

Test blasts have shown that complete removal of stemming in the last row is more effective at reducing dilatation (stretching and expansion), which helps to accurately determine the berm width and reduce wall breaking.

A minimum of 5-6 rows of regular trapezoidal shaped blastholes should be provided for near-wall blasts. It is important that all rows conform to the top edge line design to ensure rational energy distribution during the blast process.

While Fortis Extra has been shown to be highly effective in conventional vertical-blasthole blasting, it is not as effective in near-wall blasts. A lower energy density explosive should be used for the last two or three buffer rows.

One of the key aspects in improving the quality of drilling-blasting operations is to rationalize the stemming. Currently, the materials used for stemming are characterized by high coarseness, with maximum fraction sizes up to 60 mm and content of fine particles. For 165 and 216 mm diameter blastholes, the most suitable material for stemming is crushed filler of fraction 5-20 mm. This makes it possible to significantly increase the efficiency of blasting operations.

The high-impact explosive energy concentration, as shown by studies, is observed in vertical blastholes and around the mined-out quarry space. The processed results of the 460-037 test blast, obtained using the Datablast software, are presented in Figure 6.

Analysis of the blast results shows that significant rock movement causes the benches to fill with rock, which creates a danger, especially if the ore or host rock moves into the mined-out space of the quarry. This phenomenon can cause losses and dilution of the ore mass, reducing its quality and increasing additional processing costs. To minimize rock movement on empty areas of the quarry, it is recommended to reduce the specific explosive consumption around the slopes. This can be achieved by using a 3.0 m long air-cushion stemming or by using low-density explosives (1.10-1.15 g/cm³) in combination with an increased length of stemming.

(a)

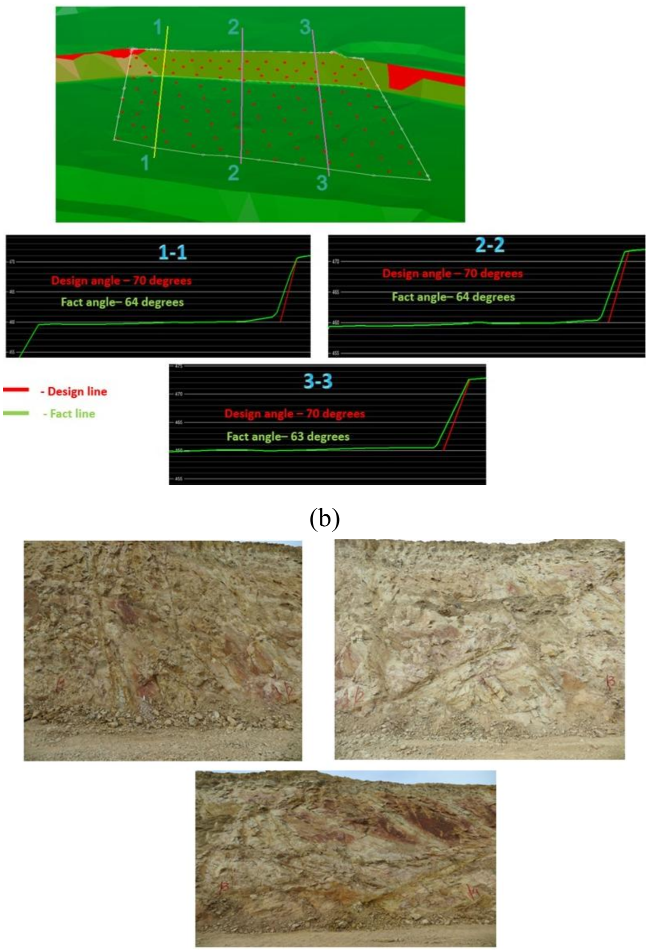


Figure 6. Effect of blasting the contour charges on the bench slope: (a) comparison of design and actual slope angles based on modeling results; (b) actual slope state after the blast at block 460-037

Based on actual LRL data and blasthole spacing in a row, the change in the volume of rock mass extracted from 1 linear meter of blasthole is calculated for different categories of rocks in terms of blastability coefficient, depending on the bench height and the diameter of the blastholes used (Table 5).

Based on these data, the graphs of change in the volume of rock mass extracted from 1 linear meter of blasthole for different categories of rocks by blastability coefficient depending on the bench height and the diameter of used blastholes have been constructed (Fig. 7).

Table 5. Change in the volume of rock mass extracted from 1 linear meter of a blasthole, depending on the bench height, blasthole diameter and the category of rocks by blastability coefficient

Category of rocks by blastability coefficient	Bench height, m	Subdrill, m	Actual LRL values, m	Rock mass yield from 1 linear meter of a blasthole, m^3	
				Blasthole diameter, mm	
				165	216
Easy-to-explode	5	0.5-0.7	7.0	32.0	36.5
Moderate-to-explode		0.7-0.8	6.5	12.5	15.0
Hard-to-explode		0.8-1.0	6.0	9.5	11.5
Easy-to-explode	10	0.7-0.8	7.5	70.5	75.0
Moderate-to-explode		0.8-1.0	7.0	39.5	43.0
Hard-to-explode		1.1-1.2	6.5	30.0	33.5
Easy-to-explode	14	1.2-1.5	9.0	93.5	100.0
Moderate-to-explode		1.5-1.9	8.0	58.5	66.0
Hard-to-explode		2.0-2.5	7.5	39.5	44.0

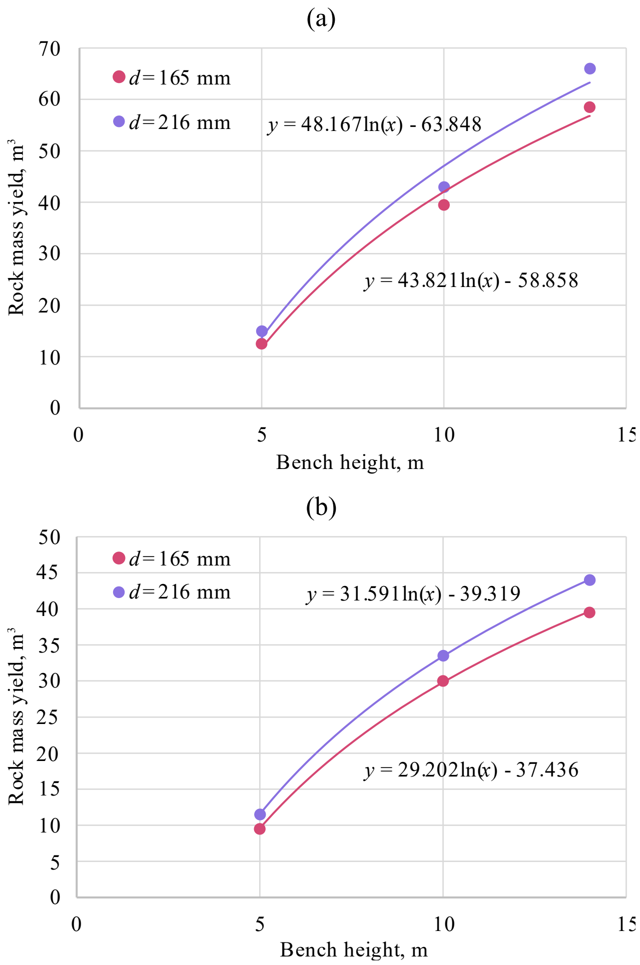


Figure 7. Dependence of rock mass yield from 1 linear meter of blasthole on bench height at different charge diameters: (a) for moderate-to-explode rocks; (b) for hard-to-explode rocks

Analysis of the graphs (Fig. 7) shows that changing the height of the bench leads to variations in the volume of rock mass extracted from one linear meter of blasthole. For each charge diameter, there is a limit value for the volume of rock mass to be extracted that can be achieved at a certain bench height. This limit is determined by the height of the bench, the characteristics of the explosive used and the physical-mechanical properties of the mass. Thus, for each bench height, the optimal charge diameter value corresponding to the category of rock to be blasted can be determined. In this case, a significant increase in the yield of rock mass from 1 linear meter of blasthole is noted. To maximize the rock mass yield, the use of optimal charge diameters is required to match specific bench heights and the physical-mechanical characteristics of blasted rocks.

Based on the conducted research, it has been found that for the Pustynnoye field, the optimal values of specific consumption of explosives, providing effective breaking of the mass and minimization of negative consequences of the blast, are: for rocks of moderate-to-explode category – 0.45 kg/m³, and for hard-to-explode rocks – 0.65 kg/m³. These parameters are characterized by the most rational blast energy distribution in the mass and correspond to the physical-mechanical properties of rocks, thereby making it possible to achieve the required level of rock mass fragmentation at minimum cost.

The conducted research and the results of test blasts became the basis for the development of an optimized drilling-blasting project aimed at improving the efficiency of blasting operations at the Pustynnoye Mine. Implementation of the proposed solutions not only improves the technological parameters of blasting, but also significantly reduces the seismic impact on the quarry near-wall zone, which contributes to improving the stability of slopes and ensuring the safety of mining operations.

The conducted research has made it possible to formulate key conclusions aimed at improving the efficiency of drilling-blasting operations at the Pustynnoye Mine of JSC AK Altynalmas.

The existing parameters of drilling-blasting operations do not fully correspond to the mining-technical conditions of the Pustynnoye field, which leads to a discrepancy between the design slope angles of the benches, disturbance of the out-contour mass and increased dilution of the rock mass with waste rock.

To improve the quality of blasting operations and reduce the seismic impact on the surrounding rock mass, it is necessary to change the technology of out-contour blasting by introducing the method of presplitting.

To determine the optimal spacing between the blastholes, it is necessary to take into account the uniform stress distribution in the bottom edge of the bench, arising from the simultaneous detonation of a series of charges. This distance is determined using the Formula: $a = W_f \sqrt{\dfrac{3W_0^2 - W_f^2}{W_0^2 + W_f^2}}$, m. This formula allows for the optimal calculation of the distance to ensure uniform distribution of blast loads and minimize the risk of non-uniform rock breaking on the edge. The character of lumpiness distribution in the blasted mass depends on the value of destructive stresses that occur in the zone of impact of blasting the blasthole explosive charges. The size of the pieces produced by crushing the rock mass can be determined using the following Expression: $e = \dfrac{l \cdot \sigma_t}{\sigma_r}$, cm.

4. Conclusions

The developed technology provides for the placement in the blasthole of single or continuous charges from priming cartridges with 0.18-0.2 diameter of the blastholes with explosive density of 1.2 g/cm³ and a detonation delay of no more than 500 ms. For out-contour blasting, it is recommended to use blastholes of reduced diameter (165 mm) and to conduct subdrill within 0.8-1.2 m depending on the strength of rocks.

The distance between blastholes and specific consumption of explosives are determined depending on the rock category, which ensures the optimal impact of the blast.

The optimal values of specific consumption of explosives for the Pustynnoye field are: for rocks of moderate-to-explode category – 0.45 kg/m³, and for hard-to-explode rocks – 0.65 kg/m³, which makes it possible to achieve the effective rock mass breaking at minimum cost.

For efficient energy distribution, the charges are compacted by reducing their size in height (65-70%), thereby preserving the required consumption of explosives and increasing the efficiency of the technology.

Optimization of the granulometric composition of the stemming, with the orientation to the fractional size of 5-20 mm, will increase the blast efficiency.

The change in the volume of rock mass extracted from 1 linear meter of a blasthole, depends on the bench height, blasthole diameter and the category of rocks by blastability coefficient. For easy-to-explode rocks at a bench height of 5 m and a diameter of 165 mm, the rock mass yield is 32.0 m^3, and for a diameter of 216 mm the yield is 36.5 m^3. This data confirms the importance of proper selection of parameters for drilling-blasting operations to optimize rock mass extraction.

The constructed dependences of the change in the volume of rock mass extracted from 1 linear meter of blasthole for different categories of rocks show that for moderate-to-explode category of rocks at a charge diameter of 216 mm, the function has the form $y = 48.17 \ln(x) - 63.85$, and for a charge diameter of 165 mm – $y = 43.82 \ln(x) - 58.86$. For hard-to-explode rocks, these dependences are expressed as $y = 31.591 \ln(x) - 39.32$ and $y = 29.20 \ln(x) - 37.44$, respectively. These results allow a more accurate selection of blast parameters depending on the bench height and rock category, which helps to optimize drilling-blasting operations and improve their efficiency.

The development of effective drilling-blasting passports aimed at optimal mineral breaking contributes to the safety of drilling-blasting operations. Implementation of these solutions provides improved rock mass crushing quality, reduced seismic impact and increased slope stability, which results in significantly improved efficiency and safety of drilling-blasting operations.

Author contributions

Conceptualization: YS; Data curation: YS; Formal analysis: BB; Funding acquisition: BB; Investigation: YS; Methodology: BB; Project administration: YS; Resources: AA; Software: AA; Supervision: YS; Validation: BB; Visualization: AA; Writing – original draft: YS; Writing – review & editing: YS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Удосконалення технології підривних робіт на золоторудних підприємствах застосуванням контурного підривання

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Мета. Розробка та обґрунтування рекомендацій щодо вдосконалення технології буропідривних робіт при відпрацюванні золоторудних родовищ відкритим способом. Дослідження спрямовані на оптимізацію параметрів буропідривних процесів з урахуванням фізико-механічних властивостей порід, умов залягання рудного масиву та вимог до якості дроблення гірничої маси.

Методика. Для дослідження застосовувалися якісні та кількісні методи аналізу. Оцінювалася відповідність технології буропідривних робіт проєктним рішенням, проводився аналіз фактичного стану уступів кар'єру та прибортового масиву після вибухів. Розроблено чисельну модель, що описує вплив контурних свердловинних зарядів на прибортовий масив, з урахуванням параметрів висоти уступу та діаметру зарядів. Особлива увага приділялася розробці рекомендацій щодо підвищення якості відбивання рудної маси, зниженню збіднення та зменшенню руйнувань прибортового масиву. Ефективність запропонованих рішень підтверджувалася за допомогою проведення серії дослідних вибухів із подальшою оцінкою їх результатів.

Результати. Результати дослідження показали, що існуючі параметри буропідривних робіт на руднику "Пустинне" не повністю відповідають гірничотехнічним умовам, що призводить до невідповідності проєктним кутам укосів та збідненню гірничої маси. Впровадження методу попереднього щілиноутворення та оптимізація параметрів зарядів дозволяють покращити якість руйнування

масиву та знизити сейсмічну дію. Отримані залежності допоможуть точно підбирати параметри вибуху, покращуючи ефективність буропідривних робіт.

Наукова новизна полягає у розробці та впровадженні комплексного підходу до оптимізації буропідривних робіт на руднику "Пустинне". В рамках дослідження визначено оптимальні параметри, включаючи діаметри бурових свердловин, зарядів для щілиноутворення, щільність вибухової речовини та гранулометричний склад вибійного матеріалу.

Практична значимість. Впровадження запропонованих методик підвищить ефективність буропідривних робіт, покращить дроблення гірничої маси, стабілізує укоси та знизить сейсмічний вплив на прибортовий масив. Оптимізація параметрів, таких як діаметри свердловин, питомі витрати вибухової речовини та щільність зарядів, знизить витрати при збереженні ефективності. Розроблені паспорти буропідривних робіт допоможуть адаптувати процеси під умови, що змінюються, та забезпечать безпеку і точність вилучення корисних копалин.

Ключові слова: *видобуток, кар'єр, уступ, підривні роботи, стабільність укосів, дроблення, гірський масив, енергія вибуху, зони руйнування*

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