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Research into mass stress and failure zone parameters during blasting of fractured high benches using blasthole charges

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Abstract

Purpose. The paper focuses on the study of the stress distribution patterns in fractured rock masses during rock breaking on high benches using blasthole explosive charges. The research aims to optimize the parameters of drilling-blasting operations through detailed analysis of stress distribution and formation of failure zones on high benches. This will significantly improve the handling equipment operating efficiency, as well as develop economically feasible blasting patterns tailored to quarry geometry.

Methods. The research is based on theoretical modeling of stress propagation caused by detonating the blasthole explosive charges in fractured rock masses. The stress distribution around the charge is calculated using equations derived from elastic deformation and surface wave theory, taking into account the particular characteristics of fractured high benches. The model includes stress propagation, wave transformation, and rock fracture behavior to identify rock crushing zones.

Findings. The results have revealed that the main factor of rock failure is tensile stress waves resulting from the reflection of compression waves. The degree of rock crushing and the volume of failure zones depend on the length and diameter of the blasthole explosive charge, the properties of the explosive agent, as well as the network of pre-existing fractures.

Originality. A new approach to studying the stress distribution in fractured rock masses during blasting operations is presented. This paper takes into account the influence of existing fractures and the interaction of stress waves with natural disturbances in the rock, thus allowing more accurate prediction of rock crushing. For the mining conditions of the Pustynnoye Deposit, the ratios between the radii of failure zones and the value of breaking stresses have been found, and a function for determining the failure radius has been proposed.

Practical implications. The results of this research can be used to optimize the parameters of blasting operations in quarries with fractured high benches. By determining the optimal sizes and placement of charges, it is possible to achieve more efficient rock crushing, reduce equipment wear and improve overall production efficiency.

Keywords: *blasting operations, mining, quarry, high benches, crushing, rock mass, blast energy, failure zones*

1. Introduction

In Kazakhstan, mining of minerals is one of the key directions of economic development [1]-[3]. The country has significant reserves of non-ferrous, ferrous, rare and precious metals, the mining of which is a priority task in the structure of the national economic complex [4], [5]. According to data from the Republican Agency for Statistics [6], by the end of last year, there was a 3.5-4.0% growth in the production of non-ferrous metals, gold by 40-50%, and aluminum by 8-11%. This growth is mainly due to increased global demand for metals and high metal prices [7]. To ensure a sustainable mineral resource base to meet the growing demand, previously unprofitable deposits characterized by high fracturing and complex structure have started to be mined [8]-[10].

Analysis of the mining practice of complex-structured ore bodies in a number of deposits, such as Sokolovo-Sarbayskoye, Akzhal, Pustynnoye, Berkara [11]-[14], has shown that during blasting operations there are significant difficulties in breaking rocks on high benches intersected by a dense network of large fractures and containing volumetric cavities. This leads to the natural rock mass disintegration into large fragments [15].

In addition, under such conditions, mass splitting is facilitated by the release of large volumes of gases (up to 800-900 l/kg on average) when using the simplest explosive agents based on ammonium nitrate [16], [17]. As a result of filling the fractures with blast gases, stresses in the mass increase up to 1.5 times, which creates difficulties in compliance with the design contour of the stope excavation, increases the value of ore losses and rock impurities on the ore-rock boundary. This ultimately reduces the mined mineral quality by 20-25%. In recent years, due to the increase in the volume of mining operations in the quarries of the above-mentioned deposits, there has been a need to significantly accelerate mining processes (accelerated mining of lower horizons). One of the key factors that ensure that mining operations remain at a high rate of decline was an increase in the height of benches to 20-25 m [18]. Blasting high benches helps to reduce the total number of blasts, simplify the organization of blasting operations, reduce the number of movements and downtime

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of equipment, as well as reduce the costs of blasting operations [19]-[21]. As a result, the performance of mining-and-transport complex and the efficiency of the enterprise as a whole are increased.

Fracturing during blast breaking of high benches has more of a negative effect on the quality of rock mass crushing than a positive one [22], [23]. This is due to the fact that under such conditions, the natural separateness confined to the interface planes results in the formation of lumps larger than the standard sizes. In addition, fracturing has a dominant effect on the granulometric composition of the rock mass when using large-diameter charges based on simplest explosive agents with ammonium nitrate (Granulites), which release significant volumes of gases [24], [25]. With increasing distance between charges, the number of vertical fractures filled with blast products increases, which leads to a worsening the degree of rock crushing [26].

In terms of mining-geological characteristics, the zone of increased rock fracturing in the listed deposits demonstrates the following data. The most unfavorable mining conditions are observed on the eastern wall of Sokolovo-Sarbayskoye Deposit, which is due to its orientation along the strike of the Eastern ore body and the highly fractured tuffites containing it [27], [28]. Six systems of tectonic fault fractures have been identified on this site. Mining-geological conditions of Akzhal Deposit and the mass state show that the stability of the quarry walls is significantly influenced by steeply-dipping fracture systems. The fractures vary in their morphological peculiarities from smooth and undulating to irregular and splintery. According to the degree of disturbance, the mass is divided into three groups: highly disturbed, severely disturbed and partially disturbed. Geologically, Berkara Deposit is represented by andesite, tufaceous sandstones, and conglomerates with interlayers of rhyolites, sandstones, siltstones [29]. These rocks within the ore field form a monoclinal fold with a rock dip of 40-45°, intensely disturbed by fault tectonics. The Mesozoic weathering crust with thickness from 3 to 25 m can also be observed in the deposit, rarely reaching 80 m in the fault zone [30]-[32].

Analysis of numerous observations and studies of blasting high benches in the above mentioned deposits indicates that regardless of the degree of mass destruction, there is always a zone of plastic deformation, which is an area of local blast impact. It has been determined that in disturbed masses, the development of fractures under the action of tensile stresses occurs with an increase in these stresses [33]. The process of mass destruction propagates both from the charge chamber to the free surface due to the concentration of stresses and deformations in the fracture zone, as well as from the free surface to the charge chamber under the impact of reflected tensile waves [34]. In the masses with intensively developed fracturing, rock crushing under the influence of tensile forces behind the front of a direct compression wave occurs only in close proximity to the charge [35]. However, observations show that the crushing process is not exclusively confined to this area, but extends further, gradually attenuating with increasing distance from the charge [36].

Vertical fractures limit the blast crushing zone, the size of which is determined by their parameters (density, openness, filling characteristic, orientation) and charge parameters (construction, specific explosive flow rate, diameter, deceleration intervals). Horizontal fractures, in turn, reduce the pressure of detonation products in the charge chamber due to its discontinuity [37], [38].

The practice of conducting blasting operations in conditions of fractured masses shows that due to the interaction of fractures, natural rock blocks are separated from each other without their sufficient crushing within the bench zone, bounded by the vertical outcropped surface and charges of the first row of blasts [39].

In the process of blasting operations, the rock mass is divided into separate blocks along the existing fractures, with pieces flying apart without complete crushing, which is due to the leakage of gaseous detonation products through the fractures [40]. This phenomenon indicates that the main blast energy loss occurs predominantly in the zones where the charge cavity intersects with horizontal fractures [41]. At the same time, the remaining part of energy is directed towards the rock mass destruction, with additional energy losses on the contacts of vertical fractures.

Despite the significant advances in the control of rock crushing using blasting operations, there remain some disadvantages associated with blasting high benches in fractured rock [42]. In particular, the stresses occurring in the rock mass during the process of blasting are not sufficiently taken into account [43]. This results in some cases in the inappropriate choice of parameters for drilling-blasting operations [44], [45].

In view of the above, our research focuses on the development of an effective methodology for measuring stresses in the rock mass during blasting operations using blasthole explosive charges in fractured masses of high benches. The obtained data can provide substantiation of optimal parameters for drilling-blasting operations, which, in turn, will lead to an increase in the technical performance of handling equipment, a reduction in losses and dilution. This will create conditions for effective management of geomechanical processes in mining as a whole.

2. Geological and technological setting

The Pustynnoye Deposit ore field is characterized by numerous discontinuous faults (Fig. 1). Fracturing is inherent in all rocks of the deposit, with open fractures in tectonic fault zones extending to a depth of 350 m. The rock mass structure is characterized by the presence of four major fracture systems: three of them are subvertical to vertical fractures, and one system includes flat-lying to moderately inclined fractures oriented in the north-western direction. In addition to these four systems, there are also single fractures with chaotic orientation [46]-[48]. The average intensity of rock mass fracturing in the above deposits ranges from 5 to 20 fractures per linear meter with the fractured layer thickness from 5 to 10 m. Such characteristics significantly complicate the process of selecting effective methods for conducting blasting operations and do not allow the required level of rock crushing to be achieved.

Pustynnoye Deposit is located in Early Permian magmatic formations that form a complexly differentiated bunch-like mass with an area of about 7.0 km². The intrusive rocks are overlain by a cover of Cenozoic sediments 0.5 to 6.0 m thick, consisting of deluvial-proluvial sediments of Upper Quaternary and modern age. At the loose section base, the Neogene sediments of the Pavlodar suite occur, which outcrop to the surface in the north-eastern and south-western areas of the ore field.

(a)

(b)

Figure 1. State of the mass of the Pustynnoye Deposit quarry benches

They are represented by red-brown and brick-red clays with gypsum inclusions, as well as thin lenses and interlayers of clayey sands of similar color, among which there are landwaste and crushed quartz. As previously noted, the ore field and deposit are intersected by multiple tectonic faults, resulting in high fracturing of all hard rocks. Open fractures, according to measurements of flowmeter and thermometry surveys, reach a depth of 30 m, and in the zones of tectonic faults – up to 350 m.

Pustynnoye Deposit quarry uses a bench-type mining system, in which mining is performed with descending horizontal layers. Overburden is transported to the outer dump and the mined ore is delivered to intermediate ore stockpiles. The main parameters of drilling-blasting operations on quarry benches, with a bench height H_{bn} = 10 m, are presented in Figure 2.

The physical-mechanical properties of the deposit rocks vary considerably, which is due to the peculiarities of its geological structure: presence of loose cover and dense rocky base, development of weakening zones (disintegrated weathered rocks and tectonic fractures), as well as a widespread manifestation of post-magmatic metasomatosis.

The cover loam density with landwaste and crushed stone inclusions ranges from 1.79 to 2.25 g/cm³, and the density of soil particles ranges from 2.7 to 2.77 g/cm³. The porosity of loose sediments is 18.2-34.0%. Groundwater filtration rate ranges from 5 to 12 min. The easily soluble salt content in loose soils is from 0.13 to 3.42% and gypsum – from 0.59 to 23.94%. The density of ore bodies (vein type) varies from 2.6 to 2.83 g/cm³. The mineral phase density is 2.77 g/cm³ and the ultimate compressive strength is 97.7 MPa.

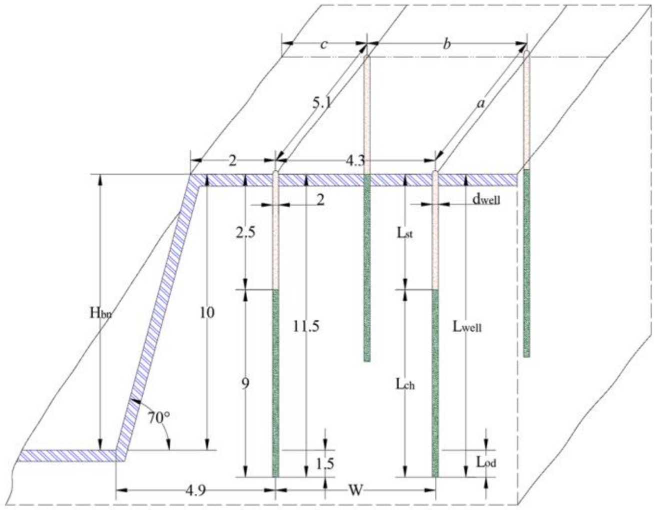

Figure 2. Main parameters of drilling-blasting operations during bench breaking (H_{bn} = 10 m) in Pustynnoye quarry

Quartz, in terms of contact strength, is a medium-hard rock and its abrasiveness is rated as above average. Among the host rocks, diorites and gabbro-diorites have the highest density (2.8-2.9 g/cm³), while weathered granodiorites have the lowest density (2.59 g/cm³). The density of the mineral component of rocks ranges from 2.75 to 2.86 g/cm³.

The strength of the deposit host rocks is determined by their lithological composition, intensity of metasomatic changes and degree of weathering. This figure varies over a wide range. The lowest uniaxial compressive strength values (σ_{com} = 16.3-59.3 MPa) are demonstrated by rocks exposed to significant weathering processes, while the strongest are slightly altered or unaltered rocks with uniaxial compressive strength (σ_{com} = 92.8-107.25 MPa).

The tensile strength of rocks within weakened zones ranges from 1 to 10.7 MPa, while for unaltered rocks this value increases to 10.9-11.2 MPa. The highest tensile strength is observed in granodiorites and diorites (11.0-11.2 MPa), while gabbro-diorites have a slightly lower strength (10.9 MPa). The rock adhesion parameters vary in the range from 19 to 30 MPa, and the internal friction angle ranges from 31.7 to 37°.

Analysis of the current state of blasting operations in Pustynnoye quarry, performed when breaking the benches 10 m high using 200 mm diameter wells, 2.5 m tamping length and specific explosive agent consumption in the range of 0.55-0.75 kg/m³, demonstrates unstable crushing results [49]. Broken ore is characterized by high hardness and abrasiveness. The lithological composition of ore is represented by sandstone with an average uniaxial compressive strength (UCS) value of about 99 MPa, ranging from 64 to 167 MPa. According to geological exploration wells, the quarry near-wall masses are composed of sandstones, quartz-bearing sandstones, siltstones, carbonaceous siltstones and serpentites. The results of observations of the blasted ore mass, both in the stockpile (Fig. 3a) and in the quarry heap (Fig. 3b), show a significant excess of the permissible rock mass size. It has been found that areas with increased yield of substandard lumps are confined to fracture zones and faults.

The ore-hosting rocks in the deposit were exposed to disintegration due to pre-ore tectonic faults of fault-shear nature, oriented in the north-western and north-eastern directions.

(a)

(b)

Figure 3. Broken and stockpiled ore mass in the Pustynnoye Deposit quarry: (a) stockpiled ore mass; (b) broken ore mass in heap

The measurement results show that the fracture dip azimuth is characterized by a steep angle in the range of 65-80° and the displacement amplitude along these faults reaches 30 m (Fig. 4).

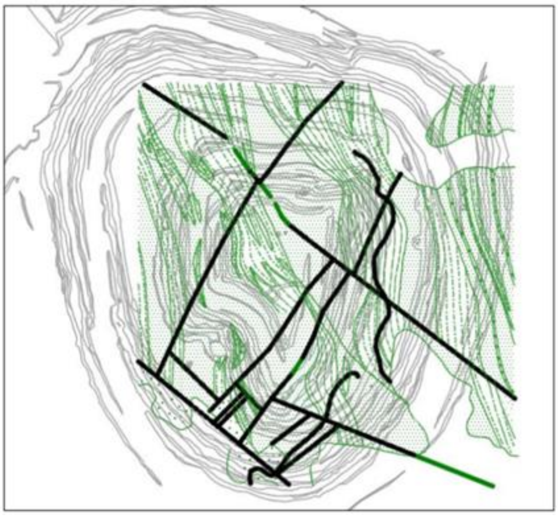

Figure 4. Scheme of propagation of the main systems of fractures and faults in the area of the Pustynnoye Deposit quarry

Most of the fractures are characterized by a steep dip with inclination angles of $\delta = 65\text{-}70°$ (22%), $\delta = 80°$ (15%) and $\delta = 75°$ (13%). There are also fractures with inclination angle of $\delta = 45°$ (12%), while less common are fractures with angles of $\delta = 5\text{-}20°$ (2-3%). Within the tectonic zones the width of fractures reaches up to 5 cm, and in some areas the mass is completely crushed and represents a loose structure.

3. Methods

When a blasthole explosive charge detonates, three characteristic zones are formed in the rocks at different distances from the charge chamber (Fig. 5):

1) rock crushing zone;

2) a zone within which a stress wave can cause irreversible changes in the form of fractures, spalling and other phenomena related to rock fracturing under conditions of high stress levels;

3) a low-stress zone where the wave does not cause irreversible deformations.

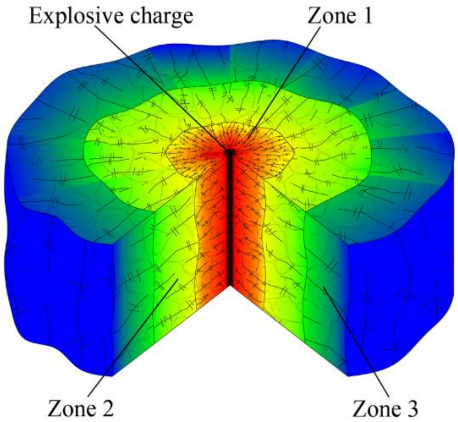

Figure 5. Characteristic blast impact zones at different distances from the charge chamber

When blasting fractured rock masses at distances greater than 10 charge radii, the stress wave does not cause further destruction until it interacts with existing fractures, faults, or the outcropped surface, where it transforms into a tensile wave. Since the tensile strength of rocks is significantly lower than that of compression, the rock failure occurs precisely under the impact of a reflected tensile wave. These failures propagate from the outcropped surface deep into the mass. The size of the failure zone caused by tensile stresses is estimated to be in the range of 60-120 charge radii. Thus, the volume of destruction within the first two zones is a relatively small part of the total volume of destruction, and for calculations it is reasonable to take into account the impact of tensile stresses, as well as to determine the degree of crushing based on the mass stress state.

When a single blasthole explosive charge detonates, at the initial moment of time the blast energy is transferred to the environment uniformly in all directions. The high-stress shock wave remains in the rock only within the zones of crushing and fracturing. Outside these zones, the wave stress intensity is below the ultimate compressive strength of the rock and, in addition, the pressure decreases rapidly due to spatial dissipation, including through fracture systems. If there is an outcropped surface within the third zone, the blast products have a concentrated impact on this surface, directed deep into the mass, causing failure and breaking of the rock through fracture systems.

Consequently, it is rational to adopt the model of impact of explosion products on the well walls (Fig. 6). In this case, the uniformly distributed pressure of blast products is replaced by equivalent resultant forces (P) directed along the four axes and applied to the center of the charge gravity.

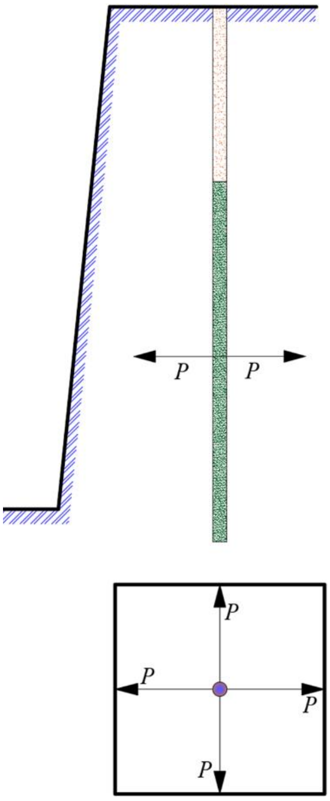

Figure 6. Scheme of acting forces during the blasthole explosive charge detonation

This scheme can be converted into a similar one, but with separate action of each force component on the half-space.

The total value of uniformly distributed pressure is equal to:

$$P_{ed} = P_{sp} \pi dL \,, \tag{1}$$

where:

P_{sp} – the specific pressure of blast products, kg/m^3;

d – is the well diameter, m;

L – is the charge length, m.

Then each component force directed in four opposite directions by absolute value is:

$$P = \frac{P_{ed}}{4} = \frac{P_{sp} \pi dL}{4} \,. \tag{2}$$

The solution to the problem of destruction of a fractured rock mass, bounded on one side by the outcrop surface and on the other side by a charge plane, is reduced to the determination of the stress state of a continuous soil half-space caused by the action of a concentrated force.

According to this theory, the stresses arising under the action of a force on the surface of a half-space can be considered as a result of the transfer of mechanical energy from the energy center to the depth of the half-space along radially diverging rays. In this case, taking into account the orientation of fractures, it can be assumed that radially diverging rays maintain a rectilinear trajectory throughout the entire length of their propagation (Fig. 7).

It is known that when an explosive charge detonates, a compression wave begins to propagate around the charge chamber, which initiates the emergence of elastic deformation energy in the medium. When this wave encounters fractures, a significant part of the elastic deformation energy is converted into kinetic energy of motion.

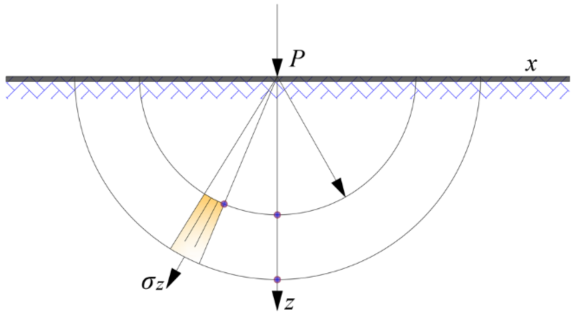

Figure 7. Stress distribution in a continuous half-space from the action of a concentrated force

This motion leads to collision of separate fragments of the medium, as a result of which the kinetic energy is again converted into the elastic deformation energy. This promotes failure not only along natural separating surfaces, but also along newly formed fractures, and is due to further transfer of elastic deformation energy to the surface energy of the fractures.

Therefore, in disturbed rocks, the absolute value of radial stresses for different points lying on the (z) axis will vary depending on the angle and depth of the point:

$$\sigma = \frac{P \cos \alpha}{2 \pi R^2} \,, \tag{3}$$

where:

P – the concentrated force acting on the half-space, kg;

R – the distance from the point of force application to the first fracture or stress measurement point, m;

α – the angle of the force application trajectory relative to the axis (z), deg.

In accordance with the above method, the stress distribution around the blasthole explosive charge can be represented as shown in Figure 8.

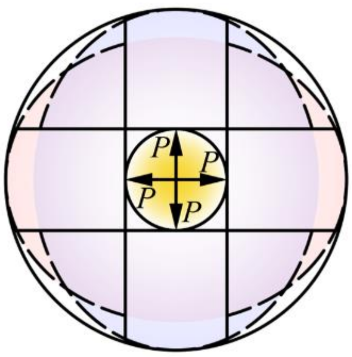

Figure 8. Stress distribution around the blasthole explosive charge

This solution is well known in the context of static loading of a system exposed to a concentrated force. To adequately analyze the tasks related to blasting destruction, it is necessary to identify the relationship between the stress state under dynamic and static loading of a given system.

The stress around the charge under the influence of the reduced forces is determined by the following Equation, based on the stress equality condition:

$$\sigma_z = \frac{P_{sp} \pi dL}{4 \cdot 2 \pi R^2} = \frac{P_{sp} dL}{8R^2} \,. \tag{4}$$

A number of researchers in the field of explosive engineering note [50], [51] that the degree of fractured rock crushing by blasting is determined by the total explosive agent energy, equal to the product of charge weight by specific blast heat.

The total blast energy in this case is:

$$Q = Q_0 \cdot c \,, \tag{5}$$

where:

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

c – the charge weight, kg.

For internal energy per unit mass of gas, there is an Expression [51]:

$$U_1 = \frac{P_1}{\rho(k-1)} \,, \tag{6}$$

where:

P_1 – the initial pressure of blast gases;

ρ – the charge density;

k – the coefficient taking into account the ratio of heat capacity of gases at constant pressure to heat capacity at constant volume, in the examined conditions can be set equal to $k = 1.2$.

Then, taking into account the coefficient (k) value, obtain:

$$P_1 = Q_{0\rho}(1.2-1) = 0.2\rho Q_0 \,. \tag{7}$$

Expression (7) is correct for charge detonation conditions in a homogeneous monolithic medium. However, when blasthole explosive charges detonate in fractured hard rock masses, the shock wave generated by the blasting process collides with the dense block boundary, resulting in an increase in pressure.

Given the necessity to express the heat of blast in mechanical units of work, obtain:

$$P_{sp} = \frac{2.4.7 \cdot \rho \cdot Q_0 \cdot 100}{1000} = 8.4 \cdot Q_0 \rho \,, \text{ MPa.} \tag{8}$$

Substituting Equation (8) into Equation (4), obtain:

$$\sigma_z = \frac{8.74 \cdot Q_0 \rho dL}{8R^2} = \frac{1.05 \cdot Q_0 \rho dL}{R^2} \,, \text{ MPa.} \tag{9}$$

Equation (9) describes the change in the stress state of the mass at its various points depending on the distance of these points to the charge, the characteristics of the explosive agent, the diameter and length of the charge.

Substituting the rupture resistance (σ_r) values of rocks by classification into Equation (9) makes it possible to determine the ultimate failure zones for fractured rocks depending on diameter and length of the charge, as well as the type of explosive agent used. As a result, Equation (9) takes the following form:

$$R = \sqrt{\frac{1.05 \cdot Q_0 \rho dL}{\sigma_r}} \,, \text{ m.} \tag{10}$$

In the context of the studied issue, one of the key tasks is to determine the boundary of a fractured mass failure under the influence of explosive charges. The solution to this problem can be performed on the basis of a plane stress state, the choice of which is conditioned by the symmetry of the studied system.

Having an equation describing the stress change around a single elongated charge, it is necessary to determine the stress distribution in the resulting field. In this research, the time factor is excluded and the solution is based on the maximum stress values, as these are the ones that lead to simultaneous material failure. Consider an arbitrary material point (A) to which the stress fields arising from two adjacent charges converge (Fig. 9).

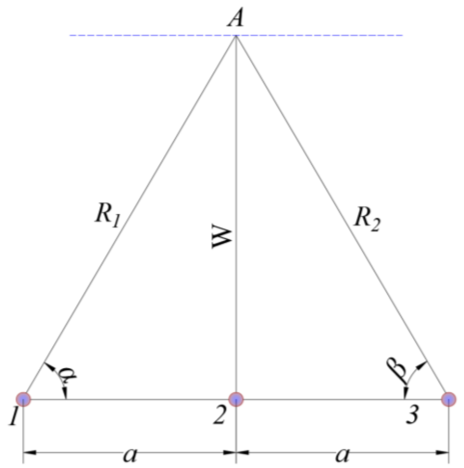

Figure 9. Scheme of stress distribution resulting from the impact of adjacent charges

The stress state at this point, caused by the influence of the left charge, is characterized by the stress components (σ_{r1}) and ($\sigma_{\theta 1}$), and from the right charge – (σ_{r2}) and ($\sigma_{\theta 2}$). The influence of each charge is considered in a separate polar coordinate system with corresponding polar angles (α) and (β).

To solve the problem, the conversion into a unified Cartesian coordinate system (xy) is performed. As a result of the joint impact of the left and right charges, the stress state at point (A) can generally be described by stress components (σ_x) and (σ_y):

$$\sigma_x = \sigma_{\theta 1}\sin^2\alpha + \sigma_{\theta 2}\sin^2\beta - \sigma_{r1}\cos^2\alpha + \sigma_{r2}\cos^2\beta \,; \tag{11}$$

$$\sigma_y = \sigma_{\theta 1}\cos^2\alpha + \sigma_{\theta 2}\cos^2\beta - \sigma_{r1}\sin^2\alpha + \sigma_{r2}\sin^2\beta \,. \tag{12}$$

To simplify the calculation, assume that the charges are located at an equal distance from the middle point, then: $R_1 = R_2$; $\sigma_{\theta 1} = \sigma_{\theta 2}$; $\sigma_{r1} = \sigma_{r2}$.

Then Equations (11) and (12) have the following form:

$$\sigma_x = 2\sigma_{\theta 1}\sin^2\alpha - 2\sigma_{r1}\cos^2\alpha \,; \tag{13}$$

$$\sigma_y = 2\sigma_{\theta 1}\cos^2\alpha - 2\sigma_{r1}\sin^2\alpha \,. \tag{14}$$

It is known that $\frac{\sigma_r}{\sigma_\theta} = \frac{1-\mu}{\mu}$, where μ – is the Poisson ratio.

It was noted earlier that the mining-geological conditions of the studied deposits, as well as physical-mechanical properties of the rock mass, are similar. In this regard, the average coefficient (μ) value can be taken as 0.3. In this case, substituting (σ_θ) in Equations (13) and (14), have:

$$\sigma_x = 2\left(0.28\sigma_{r1}\sin^2\alpha - \sigma_{r1}\cos^2\alpha\right) = 2\sigma_{r1}\left(0.28\sin^2\alpha - \cos^2\alpha\right); \tag{15}$$

$$\sigma_y = 2\left(0.28\sigma_{r1}\cos^2\alpha - \sigma_{r1}\sin^2\alpha\right) = 2\sigma_{r1}\left(0.28\cos^2\alpha - \sin^2\alpha\right). \tag{16}$$

From the scheme of stress distribution resulting from the impact of adjacent charges (Fig. 8), it can be seen that:

$$\sin\alpha = \frac{W}{R_1};\ \cos\alpha = \frac{\alpha}{R_1};\ R_1 = \sqrt{W^2+\alpha^2};$$

$$\sin\alpha = \frac{W}{\sqrt{W^2+\alpha^2}};\ \cos\alpha = \frac{a}{\sqrt{W^2+\alpha^2}}.$$

Substituting the values of sin *α* and cos *α* into Equations (15) and (16), have:

$$\sigma_x = 2\sigma_{r1}\left(0.28\frac{W^2}{W^2+a^2} - \frac{a^2}{W^2+a^2}\right) = \frac{2\sigma_{r1}}{W^2+a^2}\left(0.28W^2 - a^2\right); \quad (17)$$

$$\sigma_y = 2\sigma_{r1}\left(0.28\frac{a^2}{W^2+a^2} - \frac{W^2}{W^2+a^2}\right) = \frac{2\sigma_{r1}}{W^2+a^2}\left(0.28a^2 - W^2\right). \quad (18)$$

Thus, the stress at point (*A*) at simultaneous impact of charges is equal to:

$$\sigma_A = \sqrt{\sigma_x^2+\sigma_y^2} = \sqrt{\left(\frac{2\sigma_{r1}}{W^2+a^2}\right)^2\cdot\left(0.28W^2-a^2\right)^2 + \left(\frac{2\sigma_{r1}}{W^2+a^2}\right)^2\cdot\left(0.28a^2-W^2\right)^2} =$$
$$= \sqrt{\left(\frac{2\sigma_{r1}}{W^2+a^2}\right)^2\cdot\left[\left(0.28W^2-a^2\right)+\left(0.28a^2-W^2\right)\right]^2} = \frac{2\sigma_{r1}}{W^2+a^2}\sqrt{\left(W^2-a^2\right)^2} = \frac{2\sigma_{r1}}{W^2+a^2}\left(W^2-a^2\right) \quad (19)$$

In the considered case, the stress at point (*A*) is the sum of the stresses induced by the impact of charges 1 and 3, as well as the radial stress component generated by charge 2 (Fig. 8). Thus, the resultant stress at point (*A*) under the simultaneous impact of three charges is determined as follows:

$$\sigma_A = 2\sigma_{r1}\frac{\left(W^2-a^2\right)}{W^2+a^2} + \sigma_{r1} = \sigma_{r1}\left(2\frac{\left(W^2-a^2\right)}{W^2+a^2}+1\right) = \sigma_{r1}\left(\frac{2W^2-2a^2+W^2+a^2}{W^2+a^2}\right) = \sigma_{r1}\frac{3W^2-a^2}{W^2+a^2}. \quad (20)$$

The proposed methodology for studying the stress state during blasting of fractured masses of high benches has a universal character. The introduction into the equations of physical-mechanical rock mass properties of a particular deposit makes it possible to adapt the formulas for any rock mass characteristics and to determine the parameters of destructive stresses depending on the degree of fracturing, the bench height and the main parameters of blasthole explosive charges.

4. Results and discussion

Based on the presented methodology, the change in the rock mass stress state at different distances from the explosive agent charge is studied, taking into account the length of the charge and its influence on the stress distribution. One of the key aspects of this research is to determine the zones of ultimate rock failure, occurring depending on the charge length, and also taking into account the well filling factor. For Pustynnoye Deposit, these parameters are of great importance, since they determine the nature and intensity of rock failure during blasting operations.

In the course of the research, the methodology is used to determine the changes in the stress state of the mass at different distances from the charge, where each of the zones is analyzed in detail. An important point to note is that the charge length study is conducted at a fixed diameter, which is 200 mm. Granulite *E* has been selected as the explosive agent, which has the following characteristics: thermal effect of the blast is Q_0 = 1000 kcal/kg and density ρ = 1000 kg/m^3. These parameters are important for blasting operations, as they provide the required power and efficiency of the blast while minimizing explosive agent consumption. The research results are presented in Table 1 and in Figure 10.

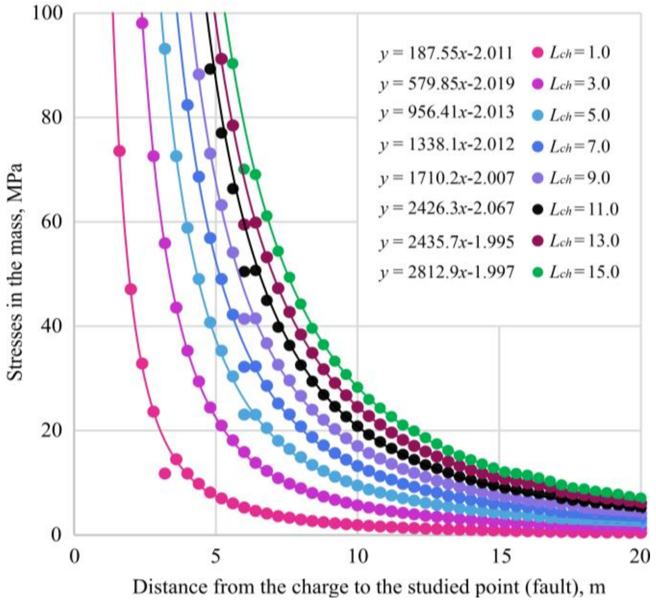

Figure 10. Distribution of stresses in the mass depending on the distance to the studied point

The graph analysis shows that for equal distances from the charge, the stress value increases proportionally to the increase in the charge, in particular its length at a constant diameter. In addition, the decrease in maximum stress values occurs more slowly the longer the charge length. According to the accepted model of rock failure under the influence of tensile stresses arising from the transformation of radial stresses on an open surface, the sizes of rock failure zones increase with increasing charge length.

Based on the obtained dependences, it has been found that under standard conditions of wave propagation and Poisson ratio of 0.3, the stress at the interface of a half-space bounded by 100r_0, in a medium penetrated by microfractures of 1 mm width, decreases relative to the initial stress at the charge-rock interface by about 500-700 times. In the case of a medium with multiple fractures wider than 2 mm, the stress at the same distance is significantly reduced. Moreover, the reduction value depends on the dynamic compressibility of the material filling the gaps between the monolithic units, as well as on the compressibility of the monoliths themselves, reaching a reduction of 100-500 times compared to the stresses in the monolithic medium.

Table 1. Variations of the mass stress state depending on the charge length at different distances from it

Ser. No.	Distance from the charge to the studied point (fault), m	Charge length, m							
		1.0	3.0	5.0	7.0	9.0	11.0	13.0	15.0
		Stresses in the mass, MPa							
1	0.4	1186.60	3550.00	5933.00	8296.40	10689.20	32656.10	15396.40	17750.00
2	0.8	294.20	887.90	1470.90	2054.00	2641.80	3232.10	3822.60	4412.90
3	1.2	131.41	392.27	657.83	921.83	1186.41	1440.38	1707.96	1961.33
4	1.6	73.55	221.79	367.75	515.85	662.95	809.05	955.15	1106.16
N + 1	N + 0.4	…	…	…	…	…	…	…	…
45	19.2	0.46	1.39	2.39	3.27	4.38	5.72	6.76	7.79
49	19.6	0.44	1.36	2.34	3.20	4.20	5.39	6.37	7.35
50	20.0	0.43	1.32	2.30	3.16	4.10	5.17	6.11	7.06

With an increase in the number of fractures and faults, there is a decrease in stress in the range of 10^6-10^{10} times, which eliminates the possibility of failure by repeated crushing of rocks under the influence of stress waves. In this case, the width of the fractures and their number reduce the parameters of stress waves nonlinearly: when the fracture width increases by 5-8 times, the stress decreases by hundreds of times.

To determine the sizes of failure zones with different physical-mechanical characteristics, including fracture systems resulting from blast impact, it is necessary to know the values of their temporary tensile strengths. Further, we determine the ultimate failure zones for fractured rocks of Pustynnoye deposit when using charges of different diameters, depending on their lengths (Table 2).

Table 2. Parameters of ultimate failure zones for fractured rocks when using charges of different diameters

Charge diameter, mm	Sizes of ultimate failure zones, m							
	Charge length, m							
	1.0	3.0	5.0	7.0	9.0	11.0	13.0	15.0
115	2.2	3.4	4.5	5.2	5.8	6.3	6.9	7.4
200	3.5	5.9	7.6	9.0	10.2	11.1	12.0	12.8
250	3.9	6.7	8.5	10.1	11.4	12.5	13.4	14.3

There are no specific recommendations in the mining-engineering literature for determining the ratios between the charge length and the bench height when breaking fractured masses. In this regard, we conduct the studies on the influence of the charge length in the well on the value of the overcome line of least resistance (LLR) W and the volume of failure zone in industrial conditions. The research results are presented in Table 3 and in Figure 11.

Table 3. Influence of blast parameters on the failure crater critical radius

Parameters	Values			
Bench height, m	7	10	12	14
Well depth, m	8.5	11.5	13.5	16
Charge weight, kg	67.5	93.5	114.2	135
Charge length, m	6.5	9	11	13
LLR value, m	4.9	4.9	7.3	7.3
Ratio of L_{ch}/L_{well}	0.76	0.78	0.82	0.87
Failure crater radius, m	5.9	6.1	5.3	5
Failure crater critical radius, m	9.4	10.3	11	11.2

As a result of the conducted research, it has been determined that the blast crater radius, as well as the failure radius and the work W value increase when the charge is lengthened by 1.2 times.

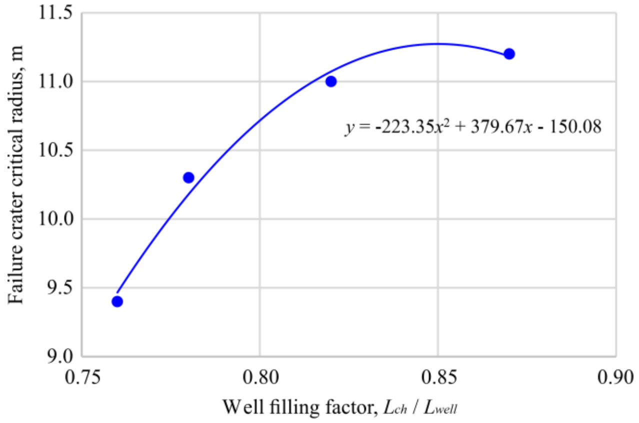

Figure 11. Dependence of the failure crater critical radius on the well filling factor

In this case, as the charge length increases up to 0.75 of the well depth, the critical failure radius increases most intensively, after which, when the charge length reaches 0.85 of the well depth, further increase becomes insignificant, and at further lengthening, these parameters remain stable. Thus, to achieve maximum failure volume and optimal rock crushing when mining high fractured benches, the most effective charge length is 0.75 of the well depth or 0.85 of the bench height.

Based on this, in calculations of the effective charge length, it is reasonable to use a value equal to 0.85 of the bench height ($L_{ch} = 0.85H$). Accordingly, Equation (10) takes the following form:

$$R = \sqrt{\frac{0.9 \cdot Q_0 \rho d H}{\sigma_r}}, \text{ m.} \quad (21)$$

Thus, based on the conducted research on the stress distribution in the mass at different distances from the charge, as well as the analysis of the sizes and configurations of failure zones, it is possible to determine the optimal parameters for placing the explosive into the well. These parameters can be set taking into account the physical-mechanical characteristics of rocks, the level of the mass fracturing and geometric peculiarities of the quarry bench. In particular, careful study of stress distributions and failure zones can not only improve the efficiency of blasting operations, but also minimize undesirable consequences such as excessive crushing or non-uniform failure, which is especially important when mining masses with complex structures. This approach makes it possible to optimize the technological parameters of drilling-blasting operations, contributing to a more accurate and cost-effective design of schemes for blasting operations, while taking into account both the geometry of the quarry and the specific properties of the mined mass.

Optimization of drilling-blasting parameters based on detailed analysis of stresses and failure zones not only improves overall efficiency of operations, but also reduces the risks associated with excessive crushing or non-uniform failure. The conducted research has confirmed that the proposed methodology for analyzing the stress distribution and failure zone sizes is universal, can be adapted to specific conditions and will help to minimize errors in designing schemes for blasting operations, by increasing their economic efficiency. Thus, further research will focus on substantiating the optimal drilling-blasting parameters based on the assessment of the stress state during blasting in fractured masses of high benches.

5. Conclusions

Blasting operations in a number of Kazakhstan deposits face serious problems due to high level of fracturing and the presence of volumetric cavities, which leads to natural rock mass disintegration into large pieces. The average intensity of fracturing in these deposits ranges from 5 to 20 fractures per linear meter, which makes it difficult to effectively crush the rock and complicates the choice of blasting methods. In addition, when using the simplest locally produced explosive agents, up to 800-900 l/kg of gases are released, which causes an increase in stresses in the mass up to 1.5 times and creates difficulties in compliance with the design contour of the quarry.

Research has shown that failures in fractured masses are initiated by tensile waves: when the charge detonates, the blast energy is distributed uniformly in all directions, but outside the failure zones, the stress rapidly decreases. Blast products have a concentrated impact on outcropped surfaces, which can cause additional failures.

In this regard, a model with equivalent resultant forces directed along four axes to the center of charge gravity is proposed to calculate the pressure and stresses. The stress state is determined based on the concentrated force acting on the half-space. The stress in the mass arising from the blast is determined by the equation taking into account the angle of force application and the distance to the fracture. The impact of the charge on the stress is described through an equation taking into account the characteristics of the explosive agents, the diameter and length of the charge.

The results show that the stress in the rock mass increases with increasing charge length at fixed diameter. This indicates the need for careful selection of charge length to control the stress level in the rock, which in turn influences the failure efficiency. The proposed methodology makes it possible to assess the stress state in fractured masses and to identify ultimate failure zones depending on the characteristics of explosive agents and geological conditions.

It has been determined that the sizes of failure zones increase with increasing charge length, which should be considered in designing schemes for blasting operations, especially in fractured rocks, where the size and shape of failure zones can vary depending on geological conditions. Research has shown that a charge length equal to 0.75 well depth or 0.85 bench height is the most effective for achieving high-quality crushing and maximum failure volume. Based on the results obtained, the ratio between the radii of failure zones and the value of breaking stresses has been found, and an empirical formula for determining the failure radius has been proposed.

At the same distance from the charge, the stress value increases proportionally to the increase in the charge length for a fixed well diameter. The failure radius depends on the well filling factor and is described by the function $y = -223.35\,x^2 + 379.67\,x - 150.08$ for deposits with similar geologic conditions.

Author contributions

Conceptualization: YS; Data curation: YI; Formal analysis: YS; Funding acquisition: YI; Investigation: YI; Methodology: YS; Project administration: YS, YI; Resources: YI; Supervision: YS; Validation: YS; Visualization: YS, YI; Writing – original draft: YS, YI; Writing – review & editing: YS, YI. 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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Дослідження напружень в масиві та параметрів зон руйнування при підриванні тріщинуватих високих уступів свердловинними зарядами

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Мета. Стаття присвячена вивченню закономірностей розподілу напружень у тріщинуватих гірських масивах при відбиванні порід на високих уступах із використанням свердловинних зарядів. Мета дослідження полягає в оптимізації параметрів буропідривних робіт за допомогою деталізованого аналізу розподілу напружень та утворення зон руйнування на високих уступах, що дозволить істотно підвищити ефективність експлуатації вантажно-транспортного обладнання, а також розробити економічно доцільні проєкти вибухових схем, адаптовані до геометрії кар'єру.

Методика. Дослідження засноване на теоретичному моделюванні поширення напружень, викликаних вибухом свердловинних зарядів у тріщинуватих гірських масивах. Розподіл напружень навколо заряду розраховується із використанням рівнянь, виведених з теорії пружних деформацій і поверхневих хвиль, з урахуванням особливостей тріщинуватих високих уступів. Модель включає поширення напружень, трансформацію хвиль і поведінку тріщин у породах для визначення зон дроблення гірської породи.

Результати. Результати показали, що основним фактором руйнування породи є розтягуючі хвилі напружень, що виникають в результаті відображення стискаючих хвиль. Ступінь дроблення породи та обсяг зон руйнування залежать від довжини і діаметру свердловинного заряду, властивостей вибухової речовини, а також мережі попередньо існуючих тріщин.

Наукова новизна. Представлено новий підхід до вивчення розподілу напружень у тріщинуватих гірських масивах при вибухових роботах. Дане дослідження враховує вплив існуючих тріщин і взаємовплив напружених хвиль з природними порушеннями в породі, що дозволяє більш точно прогнозувати дроблення гірської породи. Для умов відпрацювання родовища "Пустинне" встановлені співвідношення між радіусами зон руйнування та величиною руйнівних напружень, а також запропонована функція для визначення радіуса руйнування.

Практична значимість. Результати даного дослідження можуть бути використані для оптимізації параметрів вибухових робіт на кар'єрах з тріщинуватими високими уступами. Визначаючи оптимальні розміри і розташування зарядів, можливо досягти більш ефективного дроблення породи, зменшити знос обладнання та підвищити загальну виробничу ефективність.

Ключові слова: *підривні роботи, видобуток, кар'єр, високі уступи, дроблення, гірський масив, енергія вибуху, зони руйнування*

Publisher's note