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New theory for the rock mass destruction by blasting

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Abstract

Purpose. To develop a new theory for the rocks destruction by blasting using a description of the formation processes of zones with various mass state around the charging cavity.

Methods. The new theory for the rock mass destruction by blasting has been developed based on the use of the well-known elasticity theory laws and the main provisions of the quasi-static-wave hypothesis about the mechanism of a solid medium destruction under the blasting action. The models of zones of crumpling, intensive fragmentation and fracturing that arise around the charging cavity in the rock mass during its blasting destruction, depending on the physical and mechanical properties of the rock mass, the energy characteristics of explosives and the rock pressure impact, have been developed using the technique of mathematical modeling.

Findings. Based on the mathematical modeling results of the blasting action in a solid medium, the mathematical models have been developed of the zones of crumpling, intensive fragmentation and fracturing, which are formed around the charging cavity in a monolithic or fractured rock mass.

Originality. The rock mass destruction by blasting is realized according to the stepwise patterns of forming the zones of crumpling, intensive fragmentation and fracturing, which takes into account the physical and mechanical properties of the medium, the energy characteristics of explosives and the rock pressure impact.

Practical implications. When using the calculation results in the mathematical modeling the radii of the zones of crumpling, intensive fragmentation and fracturing in the rock mass around the charging cavity, it is possible to determine the rational distance between the blasthole charges in the blasting chart, as well as to calculate the line of least resistance for designing huge blasts.

Keywords: *rock mass, charging cavity, explosive, fragmentation zone*

1. Introduction

The mining industry is an important industry influencing the economic and technical development of countries around the world. Iron and steel industry is one of the most developed in Ukraine. The raw material base of iron and manganese ores, the development of which began at the end of the 19th century with dozens of mines and quarries, has played a major role in its origin and formation [1], [2]. Manganese ores are mined using mechanical breaking, and the extraction of iron ores is associated with the destruction of large volumes of hard rocks, the development of which requires preliminary fragmentation using drilling-and-blasting operations. Therefore, special attention of scientists and production workers is paid to the improvement and development of new methods for calculating the parameters of drilling-and-blasting operations, which will improve the performance of driving and mining operations. Another way to improve the technology of drilling-and-blasting operations is to increase the safety of blasting operations and reduce their impact on the environment by replacing TNT-based explosives with emulsion explosives (EEM) of domestic production. EEM are absolutely safe in transportation and storage [3], [4], environmentally friendly [5]-[8] and economically-viable [9], [10]. Therefore, for today one of the main problems of mining production is to increase the efficiency of a rock mass destruction by blasting with the use of EEM.

As known, a rock is a heterogeneous solid body that has a complex structure, and the mechanism of its destruction is even more complex. In general, the very mechanism of rock destruction by blasting is characterized by the short duration of loading the volume of the medium being destroyed and depends on many factors. Despite the fact that in recent years the knowledge about the nature of blasting has significantly expanded, today there is no generally accepted hypothesis about the mechanism of a rock mass destruction using blasting operations. This is due to the variety, complexity and

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rapidity of the phenomena accompanying the blasting of a solid medium [11], [12]. Based on the work [13], the phenomena of the blasting process include: detonation of an explosive charge, expansion of the charging cavity, mechanical interaction of detonation (explosion) products with a rock mass, formation and propagation of shock waves, propagation and interaction of stress waves in the rock mass and its destruction, shear of broken material and fragments distribution. As indicated in the works [11], [13] [14], today there are a large number of hypotheses explaining the physical nature of the process of a rock mass destruction by blasting, which are presented in Table 1.

Table 1. Classification of hypotheses of a rock mass destruction by blasting

Class (hypothesis of a rock mass destruction by blasting)	Author, reference	Principle of the hypothesis
Funneling	Frolov M.M., Boreskov M.M., Sukhanov A.F. [15], [16]	The destruction is accompanied by a mass part separation along the lateral surface of the blasting funnel and overcoming the gravity force by the broken rocks with the simultaneous consumption of energy for fragmentation.
Hydrodynamic	Lavrentiev M.O., Kuznetsov V.M., Vlasov O.Ye. [17], [18]	The blasting impact parameters are reduced to solving a system of differential equations, and the rock mass destruction occurs in those places where the critical velocity is higher than a certain value.
Quasi-static	Demydiuk H.P., Beliaiev O.F., Sadovskyi M.O. [19]-[21]	The main work on the rock mass destruction is performed due to the piston action of the detonation products, which destroys the rock and transfers the translational motion to it.
Energetic	Mosynets V.M., Anistratov Yu.I. [22], [23]	The medium destruction occurs as a result of conversion of the accumulated energy into the surface energy of fractures and the penetration of explosion products into them.
Wave	Pokrovskyi H.I. [24], [25]	The rock mass destruction is caused by the action of stress waves.
Quasi-static-wave	Rzhevsskyi V.V., Melnikov M.V., Khanukaiev O.N., Drukovanyi M.F., Baum F.A., Baron L.I., Yefremov E.I., Kutter H.K. and others [26]-[33]	In the process of rocks destruction by blasting, both stress waves and the piston action of detonation products are involved.

The classification analysis of hypotheses for a rock mass destruction by blasting makes it possible to draw the following conclusions. The theoretical and experimental data accumulated for decades on the concept of the blasting action mechanism under various conditions indicate that some hypotheses to some extent contradict each other, but it does not deny the hypotheses themselves. Researchers in different ways describe the distribution of stresses and energy, the very nature of rock destruction, the formation of zones around the charging cavity. As can be seen from the classification, the wave hypothesis gives a qualitative pattern of the rocks destruction mechanism by blasting. But in recent years, many researchers hold the view that both stress waves and the action of pressure from detonation products are involved in the process of rock destruction. In general, in the modern theory of the blasting action in a solid medium, the issue of criteria for a rock mass destruction has been studied insufficiently. The views of researchers differ, mainly, on the assessment of a destruction share that is produced by the wave and quasi-static blasting action. This have resulted in a very large number of theoretical concepts and a qualitative description of the nature of a solid medium destruction. Because this largely leads to the use of a large number of empirical calculation formulas during the development and design of parameters for drilling-and-blasting operations.

The vast majority of theories and methods for calculating the parameters of drilling-and-blasting operations that are based on various hypotheses of the mechanism for a rock mass destruction by blasting, and are developed with account of the industrial TNT-based explosives' properties, do not consider the energy characteristics of EEM, which have higher energy properties than analogs of the TNT-based explosives. Therefore, based on the combined quasi-static and wave hypotheses of the blasting action in a rock mass, it is necessary to develop a theory for a rock mass destruction, which would take into account the influence of the physical and mechanical properties of the medium and the energy characteristics of the explosives.

On the basis of the above mentioned research purpose, a new theory for a rock mass destruction by blasting is proposed. To achieve the purpose, the following tasks are set:

– to analyze the methods for determining the mass destruction zones around the charging cavity;

– to systematize deformations in the rock mass around the charging cavity according to the criteria and types of the medium destruction under the blasting action;

– to perform mathematical modeling of the formation mechanism of zones of crumpling and intensive fragmentation around the charging cavity.

2. Methods

The method of mathematical modeling the mechanism for destruction of a mass around the charging cavity during its blast loading includes the following stages:

– developing the parametric schemes in relation to the medium destruction zones around the charging cavity under the blasting action;

– developing the mathematical models for the zones of crumpling, intensive fragmentation and fracturing, which are formed around the charging cavity in the rock mass under its blast loading;

– determining the dependences of the identified zones, taking into account the physical and mechanical properties of the rock mass, the energy characteristics of explosive and the rock pressure impact.

A new theory for the rocks destruction by blasting around the charging cavity has been developed with the use of the well-known elasticity theory laws and the main provisions of the quasi-static-wave hypothesis of the mechanism for destruction of a solid medium under the blasting action.

3. Results and discussion

3.1. Analysing the methods for determining the zones of a mass destruction around the charging cavity

The analysis of hypotheses describing the mechanism of a rock mass destruction by blasting makes it possible to define modern views on the blasting action in a solid medium, which are the combined action of detonation products and stress waves. These views are shared by most of the leading domestic and foreign researchers, such as V.V. Rzhevsskyi, M.V. Melnikov, O.N. Khanukaiev, M.F. Drukovanyi, F.A. Baum, L.I. Baron, E.I. Yefremov, H.K. Kutter and many others [26]-[33]. According to the main provisions of this group of views (hypothesis), after the explosive charge blasting, a compression zone is formed in the radius of the shock wave impact, where the mass is highly crushed or compacted. This zone is called the crumpling zone (Fig. 1). Subsequent to the crumpling zone, the shock wave transforms into an elastic wave, which begins to act and form a fracturing zone. After this zone, a shaking zone is formed, in which the mass is destroyed along natural fractures without fragmentation. Crumpling and fracturing zones together form a zone of controlling fragmentation. Based on the indicated provisions of the described hypothesis, many scientists have developed a large number of theories and methods for determining the size of zones. Therefore, we will analyze the existing methods for calculating the dimensions of the zones of crumpling and fracturing, which are formed around the charging cavity in accordance with the theories.

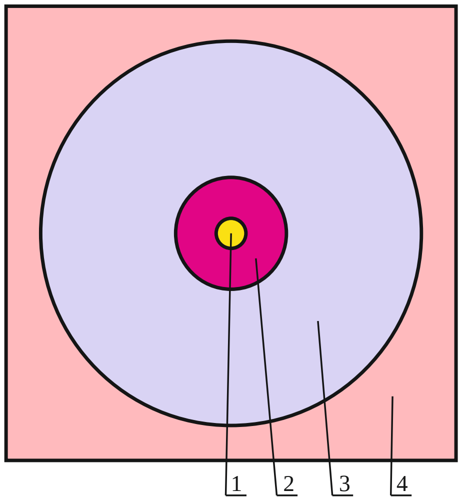

Figure 1. Zones of blasting action on the mass: 1 – charging cavity; 2 – crumpling zone; 3 – fracturing zone; 4 – shaking zone

The radius value of the crumpling zone, which is formed around the charging cavity in the rock mass under the blasting action, according to various theories is calculated by the formulas presented in Table 2.

Table 2. Methods for calculating the radius value of the crumpling zone according to different theories of the blasting action on a rock mass

Author, reference	Formula	Conventional signs
Mosynets V.M., Horbachova N.P. [22], [34], [35]	$R_{tr} = \sqrt{\frac{C_s}{C_p}} \cdot \sqrt[3]{q}$, m	C_s – shear wave propagation velocity in the mass, m/s; C_p – P-wave propagation velocity in the mass, m/s; q – charge mass in TNT equivalent, kg
Rakishev B.R. [36], [37]	$R_{zm} = r_{pr}\left(\frac{\gamma C}{5\sigma_{st}}\right)^{\frac{1}{2}}$, m	γ – rock density, kg/m^3; C – sound propagation velocity in the rock, m/s; r_{pr} – explosion cavity permissible radius, m
Szuladzinski G. [38]	$R_{zm} = \sqrt{\frac{2r_o^2 \rho_o Q_{ef}}{\sigma_{st.d}}}$, mm	r_o – charging cavity radius, mm; ρ_o – explosive density, g/mm^3; Q_{ef} –effective energy of an explosive, which is approximately 2/3 of the complete reaction heat, N·mm/g; $\sigma_{st.d}$ – dynamic ultimate compression strength of the rock, which is approximately eight times the value of the limited static compression strength, MPa
Andriievskyi O.P., Kutuzov B.M. [39], [40]	$R_{zm} = d\sqrt{\frac{\rho D^2}{8\sigma_{st}}}$, m	d – blasthole or well diameter, m; ρ – explosive charge density, kg/m^3; D – explosive detonation velocity, m/s; σ_{st} – ultimate compression strength of the rock, Pa
Djordjevic N. [41]	$R_{zm} = \frac{r_o}{\sqrt{\frac{24\sigma_{roz}}{P_v}}}$, mm	σ_{roz} – ultimate tensile strength of the rock, Pa; P_v – detonation products pressure, Pa
Kanchibotla S.S., Valery W., Morrell S. [42]	$R_{zm} = r_o\sqrt{\frac{P_d}{\sigma_{st}}}$, mm	P_d – detonation products pressure, Pa
Esen S., Onederra I. [43], [44]	$R_{zm} = 0.812 r_o (CZI)^{0.219}$, mm	CZI – destruction zone index
Chun-rui L., Li-jun K., Qing-xing Q., De-bing M., Quan-ming L., Gang X. [45]	$R_{zm} = \left(0.2\gamma\frac{C_z}{\sigma_{st}}\right)\cdot\sqrt[4]{\frac{P_b}{\sigma_o r_o}}$, m	γ – rock density, kg/m^3; C_z – sound wave propagation velocity in a rock, m/s; σ_o – triaxial rock strength, Pa
Kuznetsov V.A. [46]	$R_{zm} = 810\sqrt{\frac{\rho e}{\tau_{zd}}\cdot\frac{1-2\mu}{1-\mu}}$, m	ρ – charging density, kg/m^3; e – relative force (strength) of an explosive; μ – Poisson's ratio; τ_{zd} – ultimate shear strength of the rock, Pa
Torbica S., Lapčević V. [47], [48]	$R_{zm} = \frac{P_v r_o}{\sigma_{roz} n}\cdot\frac{(1+\mu)(1-2\mu)}{(1-\mu)}$, m	r_o – charging cavity radius, m; n – number of radial fractures for the crumpling zone n = 32 pcs.

The radius value of the fracturing zone around the charging cavity, which is formed in the rock mass during its destruction by blasting, is calculated by the formulas presented in Table 3.

Table 3. Methods for calculating the radius value of the fracturing zone in the rock mass under the blasting action according to various theories

Author, reference	Formula	Conventional signs
Mosynets V.M., Horbachova N.P. [22], [34], [35]	$R_{tr} = \sqrt{\frac{C_p}{C_s}} \cdot \sqrt[3]{q}$, m	C_s – shear wave propagation velocity in the mass, m/s; C_p – P-wave propagation velocity in the mass, m/s; q – charge mass in TNT equivalent, kg
Rakishev B.R. [36], [37]	$R_{tr} = R_{zm} \cdot \frac{\mu}{1+\mu} \cdot \frac{\sigma_{st}}{\sigma_{roz}}$, m	σ_{st} – ultimate compression strength of the rock, Pa; σ_{roz} – ultimate tensile strength of the rock, Pa; μ – Poisson's ratio
Yerofeiev I.Ye. [49]	$R_{tr} = 55 d_b \sqrt{\frac{\rho e}{\sqrt{f}}}$, m	d_b – blasthole or well diameter, m; ρ – explosive charge density, kg/m^3; f – hardness coefficient by the M.M. Protodyakonov scale of hardness; e – relative force of an explosive
Yefremov E.I., Petrenko V.D., Pastukhov A.I. [50]	$R_{tr} = \frac{\sigma_{st}}{\sigma_{roz}} r_o \sqrt{\frac{P_v}{\sigma_{st}}}$, m	r_o – charging cavity radius, m; P_v – detonation products pressure, Pa
Adushkin V.V., Spivak O.O. [51]	$R_{tr} = r_o \sqrt{\frac{P_v}{2\sigma_{roz}}}$, m	
Kexin D. [52]	$R_{tr} = 96 \left(\frac{G}{10\sigma_{st}} \right)^{\frac{1}{8}} \cdot (10E)^{\frac{1}{6}}$, mm	σ_{st} – ultimate uniaxial compression strength of the rock, MPa; E – Young's modulus of elasticity, MPa; G – loaded length, m
Kriukov H.M. [53]	$R_{tr} = 0.5 d \sqrt{\frac{P_o}{\sigma_{roz}}}$, m	d – charge diameter, m; P_o – detonation products pressure (Chapman-Jouguet point), Pa
Andriievskyi O.P., Kutuzov B.M. [54]-[56]	$R_{tr} = 0.7 R_{zm} \sqrt{\frac{\rho D^2 d}{8 \tau_{zr} R_{zm}}}$, m	d – blasthole or well diameter, m; ρ – explosive charge density, kg/m^3; D – explosive detonation velocity, m/s; τ_{zr} – ultimate shear strength of the rock, Pa
Chun-rui L., Li-jun K., Qing-xing Q., De-bing M., Quan-ming L., Gang X. [45]	$R_{tr} = r_o \sqrt{\frac{P_j}{\sigma_{roz}}}$, m	r_o – charging cavity radius, m; P_j – quasi-static pressure (pressure caused by expansion of gases), Pa
Kuznetsov V.A. [46]	$R_{tr} = 3250 \sqrt{\frac{\rho e}{\sigma_{roz}} \cdot \frac{1-2\mu}{1-\mu}}$, m	e – relative strength of an explosive
Iverson S.R., Hustrulid W.A., Johnson J.C. [57]	$R_{tr} = 25 r_o \sqrt{\frac{\rho_e e_{ANFO}}{\rho_{ANFO}}} \cdot \sqrt{\frac{2.65}{\gamma}}$, cm	r_o – blasthole radius, cm; ρ_e – explosive density, g/cm^3; e_{ANFO} – force (strength) of an explosive relative to ANFO; ρ_{ANFO} – ANFO density equal to 0.85 g/cm^3; γ – rock density, g/cm^3
Torbica S., Lapčević V. [47], [48]	$R_{tr} = \frac{P_v r_o}{\sigma_{roz} n} \cdot \frac{(1+\mu)(1-2\mu)}{(1-\mu)}$, m	n – number of radial fractures for the fracturing zone n = 4 pcs.

The analysis of the theories for calculating the radii of the zones that are formed around the charging cavity under the blasting action, makes it possible to draw the following conclusions. Almost all of the existing methods have empirical nature and are strongly dependent on certain mining-and-geological conditions for which they have been proposed. But at the same time, theoretical methods have limited applicability. Based on the analysis of the above methods, some of them are used only for monolithic mass. It has been also determined that the above methods do not take into account the change in the physical and mechanical properties of rocks influenced by the rock pressure. This suggests that most of the methods have been developed for the conditions of drilling-and-blasting operations in surface mining. Also, in some formulas for calculating the zones, the coefficients of the relative force of explosives are given, but they are intended for the use of mechanical explosive mixtures, and not at all for EEM. Therefore, the result of determining the value of the fracture formation radius may give an error. All the above methods are intended to calculate only two zones – crumpling and fracturing, but these methods do not allow calculating the zone of intensive fragmentation, which retains the pressure of detonation products, that is, mechanical compression stresses.

According to the results of theoretical and experimental studies, the most efficient is the theory and its calculation method, which was developed by O.P. Andriievskyi and B.M. Kutuzov [58]. Thanks to the obtained patterns of the crumpling and fracturing zones formation in a rock mass when exposed to blasting, the authors make this discovery [59]. Using this method, they have developed new technologies for drilling-and-blasting operations, both during underground mining and during longwall face extraction of ore. The developed technologies have been extensively tested in a wide variety of mining-and-geological conditions of mining enterprises. But, despite the good results in practical use, this method does not take into account the energy characteristics of EEM, and also requires clarification when designing the parameters for drilling-and-blasting operations in rocks with a strength below 60 MPa.

The modern theory of the rocks destruction by blasting, presented by Serbian scientists S. Torbica and V. Lapčević [47], [48] makes it possible to assess the length and density of radial fractures caused by the initiation of an explosive charge. Based on this theory, a method is proposed for determining the size of the explosion zone and quantifying the rock mass properties. According to the number of radial fractures (*n*) in the zones that are formed around the charging cavity, the authors recommend to calculate the radii of the crumpling zone (n = 32 pcs.) and fracturing zone (n = 4 pcs.). But using this method, it is also possible to calculate the radius of the zone of intensive fragmentation, in which from 8 to 12 radial fractures will form.

3.2. Systematization of deformation types in the rock mass under the blasting action, which are formed around the charging cavity, in terms of criteria and types of the medium destruction

It is well known that blasting of an extended explosive charge in an unrestricted medium surrounding the charging cavity results in the zones of blasting action such as crumpling, radial fractures and elastic deformations. The performed analysis of the theories and methods for calculating the sizes of these zones made it possible to calculate the rational parameters of drilling-and-blasting operations. Thus, the researchers, in accordance with various criteria of the medium destruction, have determined the patterns of formation of only two zones– crumpling and fracturing [34]-[38], without taking into account the formation of a transition zone – intensive fragmentation –between these zones. Therefore, let us consider in more detail the mechanism of rocks destruction around the charging cavity from the point of view of criteria and types of the medium destruction.

As it is known from the theory of the blasting action [33] and in accordance with the works [24], [25], a shock wave is formed in the rock after the explosive detonation due to the pressure of the detonation products. In the radius of the shock wave impact, a compression zone is formed, in which the rock is exposed to plastic deformation and a crumpling zone is formed (Fig. 2).

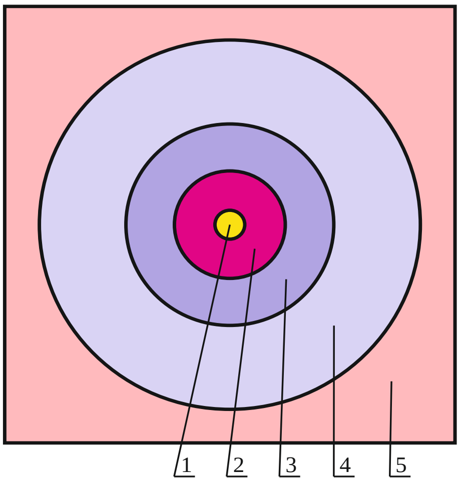

Figure 2. Zones of blasting action on the mass, which are formed around the charging cavity: 1 – charging cavity; 2 – crumpling zone; 3 – zone of intensive fragmentation; 4 – fracturing zone; 5 – shaking zone

In this zone, according to the works [60], [61], the rock changes its structure and there is an intensive fine-dispersed fragmentation of it into particles up to 1 mm. V.M. Rodionov [62] believes that at the contact of rocks and explosives, their brittle failure occurs, and as a failure criterion he takes the ultimate strength of the medium under all-around dynamic loading. It is indicated in the work of K. Johanson and P. Person [63], that the destruction of the medium near the contact of explosive and the rock is determined by the most important stress σ_1 and the difference between it and the smallest principal stress σ_3. Thus, O.P. Andriievskyi and B.M. Kutuzov [58] have scientifically substantiated the failure criterion of the medium by blasting. They argue that to determine the radius of the zone of plastic deformations arising within the crumpling zone around the charging cavity, it is necessary to use the condition under which the equivalent stress is equal to the triaxial compression stress, that is, $[\sigma_{ekv}] = \sigma_1 - \sigma_3 = \sigma_{st}$, taking into account the shock impact of the explosion products load.

With distance from the charging cavity, the shock wave transforms into a stress wave, which propagates at a sound velocity. After the crumpling zone, a rock fragmentation zone is formed, in which elastic-plastic deformations occur. V.V. Rzhevsskyi states in [33] that in this zone the energy of blasting is spent on the resistance of rocks to shear, tension, and partially compression. At the same time, H.I. Pokrovskyi in his work [25] notes that after the compacted rock layer is formed around the charging cavity (crumpling zone), a zone appears which is permeated by radial fractures in the form of rays, between which there are fractures perpendicular to the radii. These fractures occur when the pressure of the explosion products decreases, and there is a slight displacement of the rock back towards the blasting center. Based on this, the fragmentation zone can be divided into two zones: intensive fragmentation, in which compression stresses arise under the pressure of the explosion products, and the fracturing zone itself, where the rock will deform under the action of shear and tensile stresses. Further, the wave of mechanical stresses transforms into a seismic wave, which does not destroy the mass, but only shakes it, therefore, a shaking zone appears after the fracturing zone [22], [25], [33]. In the shaking zone, the destruction of the rock also occurs along natural fractures, without the destruction of the mass into fragments. Based on the analysis of the rock destruction process by blasting action, the final gradation of the zones that are formed around the charging cavity is performed, presented in Table 4.

Table 4. Detailing the zones that are formed around the charging cavity

Zone	Wave	Deformations	Destruction
First	Shock	Plastic	Crumpling
Second	Stress	Elastic-plastic	Intensive fragmentation
Third			Fracturing
Fourth	Seismic	Elastic	Shaking

3.3. Mathematical modeling of the mechanism of crumpling and fragmentation zones formation around the charging cavity

After the shock transformation of the explosive charge, which is located in the charging cavity, a shock wave will propagate in all directions of the rock mass. A certain volume of rock, which is at a small distance from the charging cavity, will be compressed in the normal direction and stretched in the tangential direction. At the front of this zone, the wave of mechanical stresses will exceed the modulus of the medium volumetric compression, therefore, the rock near the charge breaks down, creating a zone of plastic deformation, the so-called crumpling zone. To determine the radius of this zone, let us use the parametric scheme shown in Figure 3.

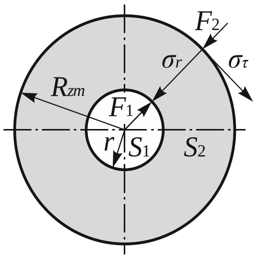

Figure 3. Parametric scheme for determining the crumpling zone, which is formed around the charging cavity when the explosive charge is detonated

To determine the crumpling zone radius R_{zm}, it is necessary to find the mechanical stresses σ, which arise in the area S_2, when exposed to pressure within the area S_1.

Pressure in area S_1, which is formed by explosion products:

$$P_1 = \frac{F_1}{S_1}, \text{ N/m}^2, \tag{1}$$

where:

F_1 – force acting on the walls of the charging cavity, according to the Equation (1):

$$F_1 = P_1 \cdot S_1, \text{ N}, \tag{2}$$

where:

S_1 – charging cavity area:

$$S_1 = \pi \cdot r^2, \text{ m}^2, \tag{3}$$

where:

r – charging cavity radius, m.

Stresses acting in the rock mass with the area S_2:

$$\sigma = \frac{F_2}{S_2}, \text{ N/m}^2, \tag{4}$$

where:

F_2 – force acting in the rock mass area S_2 and directed towards the walls of the charging cavity, according to Equation (4):

$$F_2 = \sigma \cdot S_2, \text{ N}, \tag{5}$$

where:

S_2 – area of a rock mass in which stresses act when pressure occurs in the area S_1:

$$S_2 = \pi \cdot \left(R_{zm}^2 - r^2\right), \text{ m}^2. \tag{6}$$

The F_2 force balances the P_1 pressure, which creates the force F_1. Therefore, according to Newton third law, we equate these forces $F_2 = F_1$ and obtain:

$$\sigma \cdot \pi \cdot \left(R_{zm}^2 - r^2\right) = P_1 \cdot \pi \cdot r^2,$$

or

$$\sigma = \frac{P_1 \cdot r^2}{R_{zm}^2 - r^2}, \text{ N/m}^2. \tag{7}$$

Equation (7) is G. Lamé task Formula [64], according to the theory of which, when calculating thick-walled cylinders and provided only the internal pressure impact, the radial stresses σ_r in all points of the cylinder will be negative (compression stress), and the stresses σ_τ will be positive (tensile stress). That is, the stresses σ_r and σ_τ are the principal stresses.

To determine the equivalent stress σ_{ekv} in volumetric stress state, we will use the maximum shear stress theory [65], which is well confirmed by experiments for materials that react in the same way to tension and compression.

Principal stresses:

$$\sigma_1 = \sigma_\tau = \frac{P_1 \cdot r^2}{R_{zm}^2 - r^2};$$

$$\sigma_2 = \sigma_z = 0;$$

$$\sigma_3 = \sigma_r = -\frac{P_1 \cdot r^2}{R_{zm}^2 - r^2}.$$

According to the maximum shear stress theory under complex stress state, the equivalent stress is:

$$\sigma_{ekv} = \sigma_1 - \sigma_3 \le [\sigma];$$

or

$$\sigma_{ekv} = \frac{2 \cdot P_1 \cdot r^2}{R_{zm}^2 - r^2}, \text{ N/m}^2. \tag{8}$$

From Equation (8), the crumpling zone radius can be found:

$$R_{zm} = r \cdot \sqrt{\frac{2 \cdot P_1 + \sigma_{ekv}}{\sigma_{ekv}}}, \text{ m}. \tag{9}$$

Given the dynamic blasting action:

$$R_{zm} = r \cdot \sqrt{\frac{2 \cdot K_d \cdot P_1 + \sigma_{ekv}}{\sigma_{ekv}}}, \text{ m}, \tag{10}$$

where:

K_d – dynamic coefficient at blast loading, which is equal to 2 [65].

Taking into account the conditions of triaxial rocks compression $\sigma_{ekv} \le \sigma_{сж}$, we perform the necessary transformations and obtain:

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{4 \cdot P_1}{\sigma_{st}}}, \text{ m}, \tag{11}$$

where:

d – the charging cavity diameter, m;

P_1 – explosion products pressure, Pa;

σ_{st} – ultimate compression strength of the rock, Pa.

According to [66], the detonation (explosion) products pressure can be determined with sufficient accuracy as

$$P_1 = \frac{\rho \cdot D^2}{8}, \text{ Pa}, \tag{12}$$

where:

ρ – explosive density, kg/m³;

D – explosive detonation velocity, m/s.

Having substituted Equation (12) into (11), we obtain:

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{\rho \cdot D^2}{2 \cdot \sigma_{st}}}, \text{ m.} \tag{13}$$

After the crumpling zone formation and with distance from the explosive charge location, the compression stresses from the shock wave action rapidly decay and at some distance become less than the compression strength of the rock. Therefore, the rock ceases to destruct directly from the radial stresses that compress it. The decrease in the radial stresses impact leads to an increase in tangential stresses, which stretch the rock in the annular directions. The shock wave itself from the blasting action turns into a wave of stresses with the formation of the next zone – fragmentation. In this zone, the shear, tension and compression stresses act. That is, elastic-plastic deformations occur in the rock. These stresses form the next two zones – a zone of intensive fragmentation, where compression stresses act, and a fracturing zone, where shear and tensile stresses act. To determine the radius of the intensive fragmentation zone, we use parametric scheme shown in Figure 4.

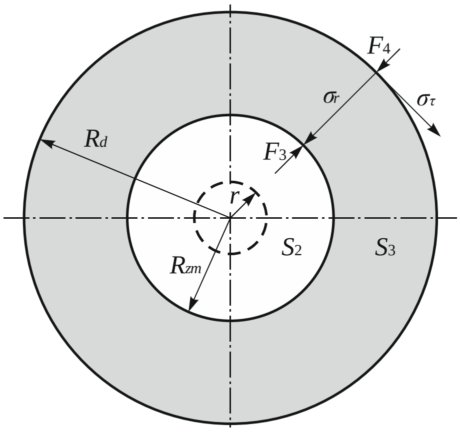

Figure 4. Parametric scheme for determining the intensive fragmentation zone, which is formed around the charging cavity when the explosive charge is detonated

To determine the intensive fragmentation zone radius R_d, it is necessary to find the mechanical stresses σ, which act within the area S_3, when exposed to pressure in the crumpling zone area S_2. The pressure in the area S_2, which acts in the crumpling zone:

$$P_2 = \frac{F_3}{S_2}, \text{ N/m}^2, \tag{14}$$

where:

F_3 – force acting on the walls of the crumpling zone, according to (14):

$$F_3 = P_2 \cdot S_2, \text{ N,} \tag{15}$$

where:

S_2 – the area of the crumpling zone formed around the charging cavity:

$$S_2 = \pi \cdot R_{zm}^2, \text{ m}^2. \tag{16}$$

Stresses acting in the area S_3 of the rock mass, around the crumpling zone:

$$\sigma = \frac{F_4}{S_3}, \text{ N/m}^2, \tag{17}$$

where:

F_4 – the force acting in the rock mass area S_3 and directed towards the walls of the crumpling zone according to (17):

$$F_4 = \sigma \cdot S_3, \text{ N,} \tag{18}$$

where:

S_3 – the rock mass area in which stresses occur under the action of pressure in the area S_2:

$$S_3 = \pi \cdot \left(R_d^2 - R_{zm}^2\right), \text{ m}^2. \tag{19}$$

The F_4 force balances the P_2 pressure, which creates the force F_3, therefore, according to Newton third law, we equate these forces $F_4 = F_3$ and obtain:

$$\sigma \cdot \pi \cdot \left(R_d^2 - R_{zm}^2\right) = P_2 \cdot \pi \cdot R_{zm}^2,$$

or

$$\sigma = \frac{P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2}, \text{ N/m}^2. \tag{20}$$

Equation (20) is G. Lamé task formula for calculating thick-walled cylinders [64]. To determine the equivalent stress σ_{ekv} in volumetric stress state, we will use the maximum shear stress theory.

Principal stresses:

$$\sigma_1 = \sigma_\tau = \frac{P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2};$$

$$\sigma_2 = \sigma_z = 0;$$

$$\sigma_3 = \sigma_r = -\frac{P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2}.$$

A stress wave passes through the zone that is formed after the crumpling zone, and elastic-plastic deformations occur in the mass due to the action of stresses on compression, tension and shear. That is, after the shock wave transforms into the stress wave, first, compression stresses act and a zone of intensive fragmentation is formed. Then, after the stress wave passes through the mass, fractures begin to form, caused by tensile and shear stresses, after which a fracturing zone begins to form.

Therefore, to determine the fragmentation zone, according to the maximum shear stress theory, we find the equivalent stress:

$$\sigma_{ekv} = \sigma_1 - \sigma_3 \le [\sigma],$$

or

$$\sigma_{ekv} = \frac{2P_2 \cdot R_{zm}^2}{R_d^2 - R_{zm}^2}, \text{ N/m}^2. \tag{21}$$

From Equation (21), the radius value of the intensive fragmentation zone can be found:

$$R_d = R_{zm} \cdot \sqrt{1 + \frac{2 \cdot P_2}{\sigma_{ekv}}}, \text{ m.} \tag{22}$$

Given that the rock in the crumpling zone transfers the pressure, which is created by the explosion products in the charging cavity to the adjacent zone, a decrease in pressure acting on the rock mass due to the increase in the contact area [36] is determined by the Formula [58]:

$$P_2 = \frac{P_1 \cdot r}{R_{zm}}, \text{ N/m}^2. \tag{23}$$

Having performed the necessary transformations, we obtain the formula for determining the radius of the intensive fragmentation zone:

$$R_d = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot \sigma_{st}}}, \text{ m.} \tag{24}$$

To determine the radius of fracturing zone, we use parametric scheme shown in Figure 5.

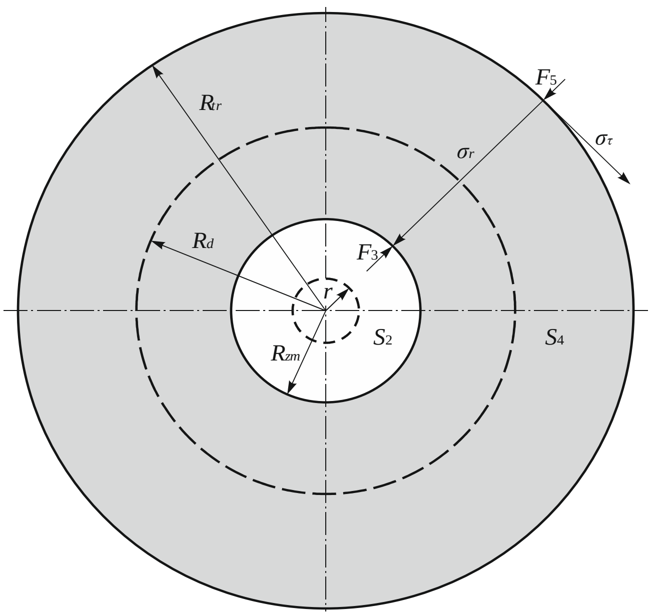

Figure 5. Parametric scheme for determining the fracturing zone, which is formed around the charging cavity when the explosive charge is detonated

To determine the fracturing zone radius R_{tr}, it is necessary to find the mechanical stresses σ, which act within the area S_4, when exposed to pressure in the crumpling zone area S_2. The pressure in the area S_2, which is formed in the crumpling zone, is determined by the Formula (14), and the force acting on the walls of the crumpling zone, by the Formula (15). The area of the crumpling zone formed around the charging cavity is determined by the Formula (16).

Stresses acting in the rock mass area S_4 around the crumpling zone:

$$\sigma = \frac{F_5}{S_4}, \text{ N/m}^2, \tag{25}$$

where:

F_4 – the force acting in the rock mass area S_4 and directed towards the walls of the crumpling zone according to (25):

$$F_5 = \sigma \cdot S_4, \text{ N,} \tag{26}$$

where:

S_4 – the rock mass area in which stresses act when the pressure arises in the area S_2:

$$S_4 = \pi \cdot \left(R_{tr}^2 - R_{zm}^2\right), \text{ m}^2. \tag{27}$$

The F_5 force balances the P_2 pressure, which creates the force F_3, therefore, according to Newton third law, we equate these forces $F_5 = F_3$ and obtain:

$$\sigma \cdot \pi \cdot \left(R_{tr}^2 - R_{zm}^2\right) = P_2 \cdot \pi \cdot R_{zm}^2,$$

or

$$\sigma = \frac{P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2}, \text{ N/m}^2. \tag{28}$$

Equation (28) is G. Lamé task Formula [64]. To determine the equivalent stress σ_{ekv} for volumetric stress state of the rocks, we will use the maximum shear stress theory.

Principal stresses:

$$\sigma_1 = \sigma_\tau = \frac{P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2};$$

$$\sigma_2 = \sigma_z = 0;$$

$$\sigma_3 = \sigma_r = -\frac{P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2}.$$

As it was noted before, a stress wave that passes through the mass forms a fragmentation zone, in which a zone of intensive fragmentation (the impact of stresses on compression) and a fracturing zone (the impact of stresses on shear) are formed. Therefore, to determine the fracturing zone according to the maximum shear stress theory, the equivalent stress is:

$$\sigma_{ekv} = \sigma_1 - \sigma_3 \le [\sigma],$$

or

$$\sigma_{ekv} = \frac{2P_2 \cdot R_{zm}^2}{R_{tr}^2 - R_{zm}^2}, \text{ N/m}^2. \tag{29}$$

From Equation (29) the radius value of the fracturing zone can be found:

$$R_{tr} = R_{zm} \cdot \sqrt{1 + \frac{2 \cdot P_2}{\sigma_{ekv}}}, \text{ m.} \tag{30}$$

A decrease in pressure acting on the rock mass due to the increase in the contact area is determined by the Formula (23).

As known from the elasticity and plasticity theory [67], if the outer diameter of the cylinder is 4 times greater than the inner diameter, and the calculations allow for a discrepancy of up to 6%, then in this case the solution is not related to the shape of the outer contour and the cylinder is in pure shear conditions. Therefore, the shear calculation is performed.

Having performed the necessary transformations, we obtain:

$$R_{tr} = R_{zm} \cdot \sqrt{1+\frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot \tau_z}}, \text{ m}, \tag{31}$$

where:

τ_z – ultimate shear strength of the rock, Pa.

In the works [68], [69], it is indicated that the main characteristics of the rock strength, such as the strength on compression, tension and shear are interrelated.

$$\tau_z = 0.5\sqrt{\sigma_{st}\sigma_{roz}}, \text{ Pa}. \tag{32}$$

The obtained Formulas (13), (24) and (31) allow calculating the radii of the zones of crumpling, intensive fragmentation and fracturing, which are formed around the charging cavity, taking into account the energy characteristics of explosives, as well as the physical and mechanical rock mass properties. But the disadvantage of these formulas is that they do not take into account the rock pressure influence. To optimize the parameters of technological processes during underground mining of ores at different depths of mining, it is necessary to know the initial stress-strain state of the virgin rock mass. Therefore, to determine the initial stress-strain state of the virgin rock mass, we use the provisions of thermodynamic (V.F. Lavrinenko) [70]-[74] and energy (O.Ye. Khomenko) [75]-[82] analytical methods for calculating the state of rocks around mine workings [83]. The compaction coefficient is chosen as the main parameter that is used when calculating the initial stress state and physical and mechanical properties of the rock mass, taking into account the depth:

$$K_u = \frac{\gamma_u}{\gamma_o}, \tag{33}$$

where:

γ_o – specific gravity of rock or ore, N/m^3:

$$\gamma_o = \gamma \cdot g, \text{ N/m}^3,$$

where:

γ – rock or ore density, kg/m^3;

g – gravitational acceleration equal to 9.81 m/s^2;

γ_u – compacted specific gravity of rock taking into account the rock pressure impact, N/m^3.

Analysis of studies performed by V.F. Lavrinenko has revealed that for every 500 m with increasing depth in the bowels of the Kryvyi Rih Basin, the density of rocks under the influence of gravity force increases by 50 kg/m^3 [70], [84]. This is confirmed by the results of research on changes in the physical and mechanical properties of rocks and ores within the Ukrainian Shield (or Ukrainian Crystalline Massif) [85]. Having approximated the maximum values using the Microsoft Excel program, an empirical dependence of the change in the increment of the specific gravity of rocks $\Delta\gamma$ on the depth H of mining operations has been obtained. For the mass of the Ukrainian Crystalline Shield, the increase in the specific gravity of the rock influenced by gravity forces, which depends on the depth of mining is:

$$\Delta\gamma = 0.1 \cdot g \cdot H, \text{ N/m}^3, \tag{34}$$

where:

H – depth of mining, m.

Based on the above, the compaction coefficient can be found:

$$K_u = \frac{\gamma_o + \Delta\gamma}{\gamma_o}. \tag{35}$$

Having substituted Equation (34) into Formula (35), a general formula can be obtained for determining the compaction coefficient:

$$K_u = \frac{\gamma_o + 0.1gH}{\gamma_o} = \frac{\gamma + 0.1H}{\gamma}. \tag{36}$$

According to the theories of thermodynamics and energy, rocks located at depth are in a compacted state due to the acting gravity forces. As known, with increasing depth, the strength of rocks increases due to a decrease in the rock pores under the action of rock pressure forces. Therefore, it is expedient to take into account the influence of rock pressure forces in the obtained Formulas (13), (24) and (31) by introducing the rock compaction coefficient, which includes the depth of mining. Formulas for calculating the radii of the zones formed around the charging cavity, taking into account the physical and mechanical rock properties, their compaction under the action of the rock pressure forces and the energy characteristics of explosives:

– for crumpling zone:

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1+\frac{\rho \cdot D^2}{2 \cdot K_u \cdot \sigma_{st}}}, \text{ m}; \tag{37}$$

– for intensive fragmentation zone:

$$R_d = R_{zm} \cdot \sqrt{1+\frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot K_u \cdot \sigma_{st}}}, \text{ m}; \tag{38}$$

– for fracturing zone:

$$R_{tr} = R_{zm} \cdot \sqrt{1+\frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot K_u \cdot \tau_z}}, \text{ m}, \tag{39}$$

where:

K_u – the coefficient that takes into account the rock compaction under the gravity forces action and corresponds to the condition $K_u \geq 1$.

Depending on the genesis, the rock mass has a certain structure and texture, which is broken by systems of randomly oriented fractures of the corresponding degree of opening. This leads to the fact that the strength characteristics of rocks in the sample and the mass have a significant difference. The decrease in the strength of rocks in the mass, which is caused by fracturing, can be quantified by the coefficient of structural weakening of a mass [86]. Formulas (37)-(39) are used when performing blasting operations in monolithic non-fractured rocks. Therefore, to improve the accuracy of calculating the radii of zones for fractured rocks, it is necessary to take into account their natural fracturing by introducing the coefficient of structural weakening of a mass into Formulas (37)-(39). Formulas for calculating the radii of the zones formed around the charging cavity, taking into account the physical and mechanical properties of rocks, their fracturing, compaction under the action of rock pressure forces and the energy characteristics of explosives:

– for the crumpling zone:

$$R_{zm} = 0.5 \cdot d \cdot \sqrt{1 + \frac{\rho \cdot D^2}{2 \cdot K_u \cdot K_s \cdot \sigma_{st}}}, \text{ m;} \quad (40)$$

– for the zone of intensive fragmentation:

$$R_d = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot K_u \cdot K_s \cdot \sigma_{st}}}, \text{ m;} \quad (41)$$

– for the fracturing zone:

$$R_{tr} = R_{zm} \cdot \sqrt{1 + \frac{\rho \cdot D^2 \cdot d}{8 \cdot R_{zm} \cdot K_u \cdot K_s \cdot \tau_z}}, \text{ m,} \quad (42)$$

where:

K_s – the coefficient of structural weakening of a mass, which can be calculated by one of the formulas given in Table 5.

Table 5. Methods for calculating the coefficient of structural weakening during breaking the rocks by blasting

Author, reference	Formula	Conventional signs
Fysenko H.L. [87]	$K_s = \frac{1}{1 + a \ln \frac{H}{l}}$	H – linear dimension of collapse, m; l – average block size (chump), m; a – the coefficient, which depends on the rock strength in the monolith and on its fracturing, which is equal to 0.5 – 10
Rats M.V. [88]	$K_s = 0.08 + 0.92\left(\frac{H}{l}\right)^{-1.2}$	
VNDMI (BNIP II-94-80)	K_s = 0.9 at l_t > 1.5 m; K_s = 0.8 at 1.0 < l_t < 1.5 m; K_s = 0.6 at 0.5 < l_t < 1.0 m; K_s = 0.4 at 0.1 < l_t < 0.5 m; K_s = 0.2 at l_t < 0.1 m	l_t – the distance between the fractures, m
Mosynets V.M., Abramov A.V. [89]	$K_s = \frac{1}{1 + 0.25\sigma_{roz} \ln \frac{W}{l_{sr}}}$	W – the line of least resistance, m; l_{sr} – the average distance between the fractures, m
Andriievskyi O.P., Kutuzov B.M.	$K_s = \frac{1}{0.97 + 0.13\frac{R_{tr}}{l_{sr}}}$	R_{tr} – the radius of the fracturing zone in the monolithic mass, m
Sdvyzhkova O.O., Shashenko O.M. [69]	$K_s = 1 - \sqrt{0.5 \cdot \eta} \cdot e^{-0.25 \cdot \eta}$	η – the coefficient of the rock mass strength variation

The numerical solution results of the obtained mathematical models for the zones are compared with the results of their calculation by the known methods from the theories [47], [58]. This makes it possible to determine the discrepancy between the calculation results, which do not exceed 1% for the crumpling and fracturing zones, and up to 9% for intensive fragmentation zone, which indicates a high reliability of the results and the correctness of the obtained mathematical models.

The proposed theory can be used to calculate the radii of the zones that are formed around the charging cavity during blasting of an extended explosive charge, both in a monolithic non-fractured and in fractured rock mass, taking into account the rock pressure action when using an explosive with different energy characteristics. The calculation results of these zones will enable designing the rational parameters for drilling-and-blasting operations, both during mine workings [90]-[92], and when performing stope operations associated with breaking the ores, according to different layouts of the wells [93], [95].

4. Conclusions

1. The dependences have been determined for the formed zones of crumpling, intensive fragmentation and fracturing, which arise around the charging cavity in a monolithic and fractured rock mass under its blast loading, taking into account the physical and mechanical properties of the medium, the energy characteristics of explosives and the rock pressure impact.

2. The dependence of the crumpling zone has been obtained, from which it follows that the radius of the crumpling zone created during blasting of an extended explosive charge is directly proportional to the charging cavity radius and the square root of the pressure, developed by the explosive detonation products, and is inversely proportional to the square root of the ultimate compression strength of the rock, compaction coefficient of the rock and coefficient of structural weakening of a mass.

3. It has been found that the radius of the intensive fragmentation zone during blasting of an extended explosive charge is directly proportional to the crumpling zone radius and the square root of the pressure of the explosive detonation products and the charging cavity diameter. At the same time, it is inversely proportional to the square root of the crumpling zone radius, ultimate compression strength of the rock, compaction coefficient of the rock and coefficient of structural weakening of a mass.

4. The dependence of the fracturing zone radius during blasting of an extended explosive charge has been obtained, which is directly proportional to the crumpling zone radius and the square root of the pressure of the explosive detonation products and the charging cavity diameter. At the same time, it is inversely proportional to the square root of the radius of formed crumpling zone, the ultimate shear strength of the rock, compaction coefficient of the rock and coefficient of structural weakening of a mass.

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Нова теорія руйнування масиву порід вибухом

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Мета. Розробити нову теорію руйнування порід вибухом шляхом опису процесів формування зон різного стану масиву навколо зарядної порожнини.

Методика. Нова теорія руйнування масиву порід вибухом розроблялася на основі використання загальновідомих законів теорії пружності та основних положень квазістатично-хвильової гіпотези механізму руйнування твердого середовища під дією вибуху. Моделі зон зминання, інтенсивного подрібнення та тріщиноутворення, які виникають навколо зарядної порожнини у масиві гірських порід при його вибуховому руйнуванні, що залежать від фізико-механічних властивостей масиву, енергетичних характеристик вибухівки та дії гірського тиску, розроблені за допомогою методу математичного моделювання.

Результати. За результатами математичного моделювання дії вибуху у твердому середовищі було розроблено математичні моделі утворення зон зминання, інтенсивного подрібнення та тріщиноутворення, які формуються навколо зарядної порожнини у монолітному або тріщинуватому масиві гірських порід.

Наукова новизна. Вибухове руйнування масиву гірських порід реалізується за степеневими закономірностями утворення зони зминання, інтенсивного подрібнення та тріщиноутворення, в які комплексно враховано фізико-механічні властивості середовища, енергетичні характеристики вибухівки та дію гірського тиску.

Практична значимість. Використання результатів розрахунку при математичному моделювання радіусів зон зминання, інтенсивного подрібнення та тріщиноутворення у масиві порід навколо зарядної порожнини, дозволяє визначити раціональну відстань між шпуровими зарядами у паспортах буропідривних робіт, а також розраховувати лінію найменшого опору для проектування масових вибухів.

Ключові слова: *масив порід, зарядна порожнина, вибухова речовина, зона подрібнення*

Новая теория разрушения массива пород взрывом

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Цель. Разработать новую теорию разрушения пород взрывом путем описания процессов формирования зон различного состояния массива вокруг зарядной полости.

Методика. Новая теория разрушения массива пород взрывом разрабатывалась на основе использования общеизвестных законов теории упругости и основных положений квазистатическо-волновой гипотезы механизма разрушения твердой среды под действием взрыва. Модели зон смятия, интенсивного дробления и трещинообразования, которые возникают вокруг зарядной полости в массиве горных пород при его взрывном разрушении, зависят от физико-механических свойств массива, энергетических характеристик взрывчатого вещества и действия горного давления, разработаны с помощью метода математического моделирования.

Результаты. По результатам математического моделирования действия взрыва в твердой среде были разработаны математические модели образования зон смятия, интенсивного дробления и трещинообразования, которые формируются вокруг зарядной полости в монолитном или трещиноватом массиве горных пород.

Научная новизна. Взрывное разрушение массива горных пород реализуется степенными закономерностями образования зоны смятия, интенсивного дробления и трещинообразования, в которых комплексно учтены физико-механические свойства среды, энергетические характеристики взрывчатого вещества и действие горного давления.

Практическая значимость. Использование результатов расчета при математическом моделировании радиусов зон смятия, интенсивного дробления и трещинообразования в массиве пород вокруг зарядной полости, позволяют определить рациональное расстояние между зарядами в паспортах буровзрывных работ, а также рассчитать линию наименьшего сопротивления для проектирования массовых взрывов.

Ключевые слова: *массив пород, зарядная полость, взрывчатое вещество, зона дробления*