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Blast wave interaction during explosive detonation in a variable cross-sectional charge

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Abstract

Purpose. The research aims to assess the efficiency and performance of solid media destruction in directed blasting of a charge with variable cross-sectional shape.

Methods. Numerical modelling of the blast wave interaction process is performed using the finite element method based on the Euler-Lagrange algorithm. The Johns-Wilkins-Lee equation of state is used to determine the pressure-volume dependences of medium destruction. Assessment of solid medium destruction mechanism during a directed blasting of a charge with variable cross-sectional shape is carried out based on polarization-optical method on models made of optically active material.

Findings. Experimental studies of solid medium destruction by the action of directed blasting with a variable cross-section charge made it possible to determine the direction of blast wave propagation and its amplitude in stress wave, influencing the intensity of radial crack network formation in superposition areas, and directed perpendicularly to explosive cavity. At the same time, the average peak pressure in collision zone of two shock waves in centre of spherical cavity is approximately 1.48 and 1.84 times higher than that in weakly blast-loaded areas. It has been found that when two shock waves collide and superimpose on each other, the intensity of their impact increases. Moreover, the shock wave velocity in collision zone is higher than that of the radial shock wave.

Originality. It has been determined that the maximum pressure values on the explosive cavity wall at the initiation points sharply increase and then gradually stabilize as the blast stress waves propagate and have an arbitrary distribution pattern. Three areas should be considered: not superimposed, weakly superimposed, and strongly superimposed. At each point of detonation, the pressure on explosive cavity wall will be minimal, while in the charge centre in the spherical insert zone, on the contrary, it will be maximal. In this case, the pressure in the central superposition area is about 2.84 times greater than at the initiation ends, and the nature of distribution changes according to a linear dependence.

Practical implications. The performed research findings can serve as a basis for development of effective parameters of resource-saving methods for stripping hard rocks of complex structure in the conditions of ore mines.

Keywords: *explosive, explosive loading, solid medium, explosive charges, explosive destruction*

1. Introduction

The destruction efficiency of rocks with complex structure, which include uranium deposits of Ukraine, can be based on following unconventional technologies: thermal loading, influence of high energy particle flows. However, the use of blasting energy remains an effective way to prepare rock mass in underground mining, iron and uranium ores. Blasting in uranium ore mining should ensure sufficient volumes of rock mass for processing, economic efficiency and environmental safety of mining operations. To solve this problem, it is important to provide a detailed substantiation for choosing rational parameters of blasting operations, which should consider many factors. Complex of required measures includes the following aspects of problem-solving: organization of drilling and blasting operations, rational placement of explosive charges (explosives) in rock mass, taking into account anisotropy of its physical-mechanical properties, structural peculiarities and fracturing, substantiation and choice of explosive type, etc. Addressing these issues will reduce the output of crushed fractions and oversize, as well as increase mineral mining.

This makes it possible to increase the efficiency of drilling and blasting operations and reduce the negative impact on the environment. The latter is of particular importance when mining subsurface reserves of deposits in protected areas (housing and industrial infrastructure). Therefore, an important social and practical task that requires response and effective decision-making is the development and implementation of modern seismically safe drilling and blasting technologies.

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One of the effective ways to control rock crushing is to determine the rational construction and diameter of borehole charges, as well as its placement in the rock mass with a complex structure [1]. Therefore, the issues of seismic safety are most relevant at long-operating mining enterprises, where, due to expansion of the mining block borders in ore deposits, mining operations are close to industrial, residential buildings and structures. At the same time, significant volumes of rock mass and massif have been extracted from subsoil, which is located around the mine workings of operating block. Rock mass is exposed to high compressive stresses that increase with depth. High stresses contribute to occurrence of rock impacts and technogenic seismic disturbances (earthquakes) [2]. This is particularly the case with iron and uranium ore deposits mined in Ukraine, which are concentrated in complex deposits. They also include fields with deposits under water massifs with deposits of submarine landslide structure, zones of shallow tile stratification under industrial and civil constructions. It should be noted that the efficiency of mining in such fields depends largely on their structure, physical-mechanical properties of rocks and parameters of drilling and blasting operations, given the seismic impact of blast on protected objects. This is confirmed in the paper [3], which analyses studies of the seismic activity of blasts and their destructive impact on urban and social buildings during mining of upper horizons at depths of more than 330 m (for example, Central deposit of uranium ore, Kropivnitsky). And given that these ore bodies and rock masses have anisotropic structure, the mining of these horizons caused difficulties due to different rock properties, structure and fracturing. These factors have a major influence on seismic vibration propagation pattern in different directions from the blast site (along the strike and across the strike of ore deposit) [4].

The development of computer technologies has made it possible to develop mathematical models and calculation methods, as well as to substantiate possible disturbance parameters in underground and surface structures under the influence of seismic waves caused by underground blasts, vibration and earthquakes. Studies have shown that when assessing the development of geomechanical and seismic processes during dynamic loading of block structured rock mass, it is necessary to consider its structure as a system of nested blocks with different scale levels. Blocks are connected by interlayers consisting of weaker fractured rocks [4]. These mass peculiarities should be included in mathematical models. Dynamic behaviour block medium can be described as movement of rigid blocks due to yielding interlayers between them. The calculation model can serve as a mass grid connected with each other by springs and dampers. Finite-difference solution to the problem of dynamic impact on surface of a buried borehole charge explosive cavity (in blocky medium) is obtained within the framework of two-dimensional model. By taking into account the mass structure, its physical-mechanical properties and fracturing, the authors in the papers [5]-[7] developed a mathematical model for substantiation of charge location in the block.

Many theoretical [8] and experimental [9] studies have been devoted to the research of seismic blast impact on mine workings, as well as civil and industrial objects [7]. Research was conducted by scientists of scientific centers of Ukraine, near and far abroad [10]. Most used parameter, which is fixed experimentally and determined theoretically, is the velocity of oscillations (landslides) in the mass of protected object [9]. However, it is known that duration of different dynamic or other loads on mine workings, civil and industrial objects has a significant impact on the ultimate strength characteristics [11], [12], as well as degree of deformation and destruction of rocks influenced by seismic blast waves [13].

Paper [14] shows that for substantiation of effective parameters of drilling and blasting operations it is expedient to apply mathematical and computer modeling tools, which will enable to assess the results of blast action and optimize blast parameters. The author in [15] proposes a methodology for calculating seismically safe and optimal geometric parameters for location of blast holes in a block (well grid), and deceleration intervals when using lower and upper detonators inside borehole explosive charges. These charges cross rock mass, separated by karst cavity, which makes it possible to ensure qualitative destruction of karsted masses and reduce oversize yield.

It is known that when cylindrical explosive charges are detonated, seismic blast waves excite vibrations on open surfaces of working and non-working benches, quarry walls, mine workings, mining blocks at mines, industrial and residential buildings, as well as different structures on the surface and in depth of the mass.

Under action of detonation and shock waves, a field of stress waves is formed in the rock mass. The nature of stress waves and propagation direction depend on position of explosive charge initiation point. This has an impact on quality and efficiency of rock crushing.

The following variants of initiation point location are used: forward, reverse and towards each other [16]-[19]. Moreover, the explosive detonates completely in a short period of time. Therefore, it is necessary to study wave processes of the blast and stress field distribution for explosive located in charge column of variable cross-section and initiated from both ends. The influence of initiation point location on the blast effect can be studied by physical tests on block model samples and numerical modeling of explosion processes in such a charge. Zhang et al. [20]-[22] proposed a blast initiation method using several techniques based on the principle of shock wave collision at collision points. Wave interaction effect can be used to form a shielding zone at ore stripping sites in ore deposit chamber. This can reduce seismic impact of blast waves on protected objects located on the surface.

Research results show that process of medium destruction under tension and compression can be modeled using the finite element method. In this case, the influence of different positions of initiation points on blast results is assessed using an experimental bench. Gao et al. [23], [24] studied effects of rock crushing at different initiation points and found that the blast impact on the destructed medium at lower initiation point is 61.3 less than at upper one. Miao et al. [25], [26] propose a new method called symmetric bilinear point initiation system using the principle of shock wave collision. It has been determined that this effect increases rock crushing quality. Haeri et al. [27] studied the influence of crack position on destruction trajectory of double-fractured beam specimens taken from bridge spans.

The problem between tiered collapse of overhanging roof can be effectively solved by multi-point initiation. Leng et al. [28], [29] analyzed the tensile and shear destruction zones in blasted media under different initiation modes. Results show that in practical blasting operations, the space distribution of blast energy can be controlled by varying number of initiation points. I.A. Onederra et al. [30] propose a hybrid model of a stressed blast and combined it with experimental results, thus indicating that disturbance range of blast hole bottom is much smaller than its mouth when initiated from below. Liu et al. [31] developed and designed tensile and compressive damage models using the finite element method, and then assessed the influence of different initiation point positions on the solid medium destruction using an experimental bench. To study blast wave field, Zuo et al. [32], [33] analyze characteristics of blast shock wave propagation and gaseous detonation products when a cylindrical charge is initiated at its end and center. They have found that range of medium destruction at each initiation mode is about five times of explosive cavity diameter. Authors analyzed parameters that describe blast waves during the blast action in a dispersed charge. Yang et al. [34] studied blast wave field propagation when blasting shaped charge and obtained characteristics of blast shock wave formation in frontal and vertical directions. They have determined that blast shock wave intensity in frontal direction is 2.3 times higher than shock wave intensity in vertical direction. Gerasimov et al. [35] use the polarization-optical method to study shock wave formation as a result of blasting. Authors obtained a reference for observing blast shock wave propagation in space, made energy assessment and determined parameters. This study uses the principle of two oppositely propagating shock waves colliding from explosive charge detonation to obtain a structural diagram of main characteristics of shock wave collision using Hugoniot curves. Experiments use a high-speed experimental system, which includes a model made of optically active material (organic glass), along length of which the explosive cavity is drilled. Explosive material is then placed in cavity and initiated from ends. Shock wave collision process and impact wave formation in whole explosive cavity were investigated. A mechanical model of shock wave collision with the explosive cavity wall was developed and force fields of stresses in explosive cavity collision area were analyzed. A simulation model was created, development processes of maximum stress fields and damage to specimen were analyzed, and dependences of pressure distribution on explosive cavity walls were plotted.

Thus, new effective methods of drilling and blasting operation management, aimed at reducing negative impact on protected surface objects and main mine workings, increasing mining intensity, reducing oversize output, ore depletion, using effect of rock destruction by blasting the explosives charge of variable cross-section with initiation from both ends at the end of borehole, are still relevant today. All this contributes to the change in the direction and focusing of stress waves on the walls of blast hole in the shock wave collision zone (with subsequent propagation of radial cracks deep into the mass and formation of a protective zone in the ore deposit block in the contact zone between blast chamber and backfill mass). Such approach allows a reasonable choice of effective parameters of spatial location of explosive wells (diameter, length, and distance between wells in a fan and between fans) in a production block of the ore deposit and to correct drilling and blasting operation parameters.

2. Methods

Previous studies have determined that stresses and particle velocity on the collision surface, as well as the stress state at the collision of two shock waves in a point of spherical surface location corresponds to intersection of Hugoniot *p-u* curves [16], [36].

The Hugoniot curve of a shock wave can be described by Equation:

$$P=\rho_0 C_0\left(u-u_0\right)+\rho_0 s\left(u-u_0\right)^2, \quad (1)$$

where:

C_0 – is a sound velocity in the medium, m/s;
s – empirical constant;
u – particle velocity, m/s;
u_0 – initial particle velocity, m/s;
ρ_0 – initial density, kg/m^3.

At initial moment of time $u_0 = 0$, and for the left (S_1) and right (S_2) shock waves propagating towards each other, the following can be written, respectively:

$$\rho_0 s u^2+\rho_0 C_0 u-P_1=0; \quad (2)$$

$$\rho_0 s u^2+\rho_0 C_0 u-P_2=0. \quad (3)$$

From Equations (2) and (3) we obtain:

$$u_1=\frac{-C_0+\sqrt{C_0^2+4sP_1}}{2s}; \quad (4)$$

$$u_2=\frac{-C_0+\sqrt{C_0^2+4sP_2}}{2s}. \quad (5)$$

When shock waves S_1 and S_2 pass through $P = 0$, Hugoniot curves can be expressed as follows:

$$P_1=\rho_0 C_0\left(2u_1-u\right)+\rho_0 s\left(2u_1-u\right)^2; \quad (6)$$

$$P_2=\rho_0 C_0\left(2u_2-u\right)+\rho_0 s\left(2u_2-u\right)^2. \quad (7)$$

Based on superposition curve, particle propagation velocity u_3 at the point of intersection and collisions of shock waves is expressed as follows:

$$u_3=u_1+u_2. \quad (8)$$

Pressure P_3 at interface can be obtained by substituting Equation (8) into Equations (6) and (7):

$$P_3=\rho_0 C_0\left(2u_1-u_3\right)+\rho_0 s\left(2u_1-u_3\right)^2; \quad (9)$$

$$P_3-(P_1+P_2)=-2\rho_0 u_2\left(C_0+su_1\right). \quad (10)$$

According to Equation (3), $u_2 < 0$ and $C_0 + Su_1 > 0$. Therefore, Equation (10) takes form:

$$P_3>\left(P_1+P_2\right). \quad (11)$$

In particular, when $P_1 = P_2$, $u_1 = -u_2$, $u_3 = 0$:

$$P_3>2P_1. \quad (12)$$

After shock waves collide, intensity of resulting shock wave on inner collision surface (spherical insert) exceeds sum of two shock wave intensities instead of simple linear superposition. Figure 1 shows convergence and summation of shock waves during explosive detonation from both ends.

Total energy E_T of explosive consists of potential energy E_P and kinetic energy E_K [37].

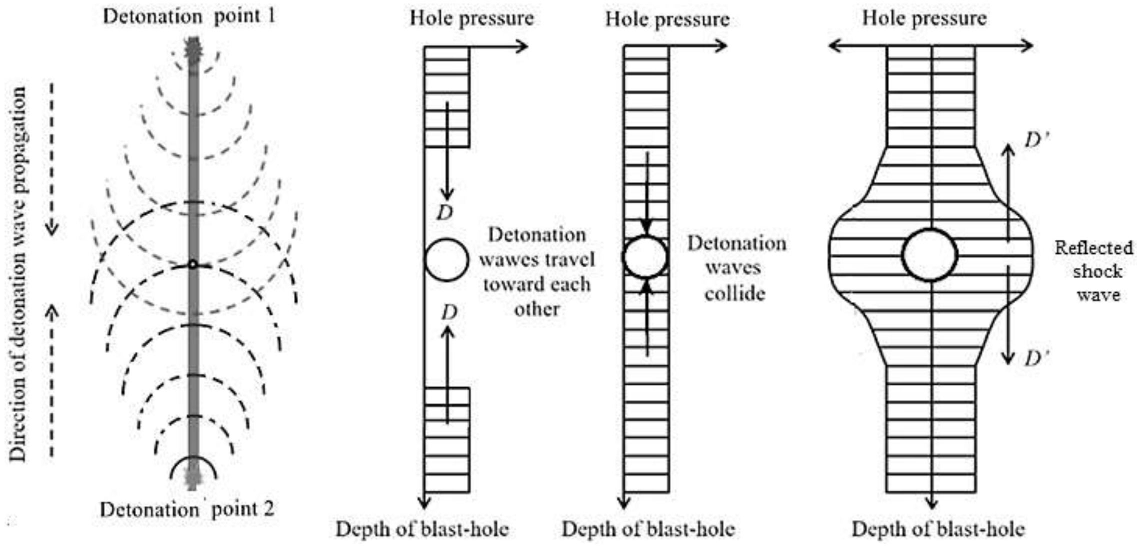

Figure 1. Interaction of shock waves at counter initiation in variable cross-sectional charge

In terms of energy conservation we have:

$$E_T = E_P + E_K = \frac{P}{\gamma - 1} + \frac{1}{2}\rho u^2, \qquad (13)$$

where:

γ – adiabatic coefficient;

first summand – potential energy (pressure energy);

second summand – kinetic energy.

Pressure energy contributes to rock destructive ability. When two shock waves move towards each other, particle velocity on inner surface of collision-spherical insert $u_3 = u_1 + u_2 = 0$, and pressure increases to P_3. According to equation of energy conservation, kinetic energy is converted to potential energy as particle velocity decreases and ability to destroy rock increases.

Blast waves transmitted in opposite directions form a high-intensity shock wave. In collision superposition area, superimposed explosive shock wave has a linear shape (Fig. 2).

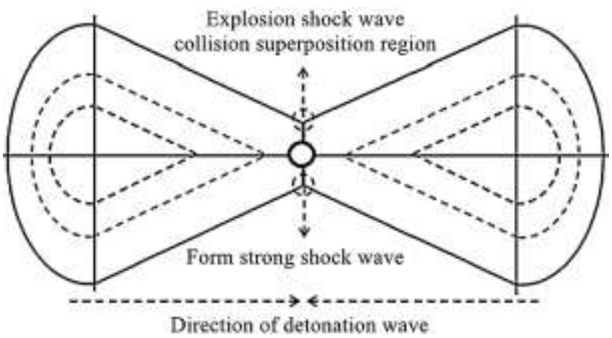

Figure 2. Scheme of blast shock wave collision area during detonation of a variable cross-sectional charge

In this case, intensity of the superposed shock wave on collision surface exceeds the sum of two shock wave intensities after their head-on collision. Superimposed shock wave on collision surface acts on the explosive cavity wall, increasing damage. Figure 3 shows interaction between blast shock waves and explosive cavity wall.

As illustrated schematically in Figure 3, shock waves propagate towards each other at an angle α. Angle between front of each shock wave and blast hole wall is equal to β. Pressure angle on blast hole wall subjected to shock wave loading is δ.

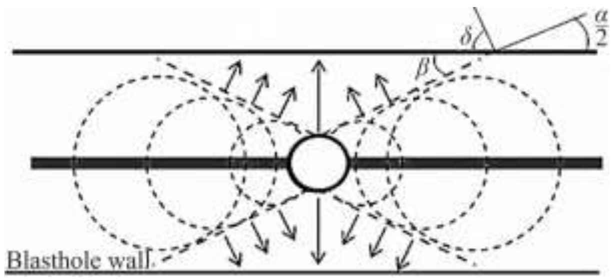

Figure 3. Superimposed blast shock wave acting on explosive cavity walls

Connection between the angles α, β and δ is as follows:

$$\delta = 90^\circ - \beta = 90^\circ - \frac{1}{2}\alpha \,. \qquad (14)$$

After explosive detonation, blast waves from both ends of the variable cross-sectional charge are compressed and form 90° angle of incidence to explosive cavity wall in loaded area.

Let σ be a stress state at any point. Let $\sigma_{\Theta 1}$ (compressive stress) and σ_{t1} (tensile stress) be the stresses generated by shock wave from the right side of explosive cavity walls. Then, the stress formed by shock wave from the left on explosive cavity walls will be denoted as $\sigma_{\Theta 2}$ (compressive stress) and σ_{t2} (tensile stress), respectively. Based on conditions of stress displacement, stress state on explosive cavity wall in finite displacement area is characterised by compressive σ_Θ and tensile σ_t stresses.

The stress state in displacement area can be represented in vector form:

$$\begin{cases} \sigma_{\theta'} = \sqrt{|\sigma_{\theta 1}|^2 + |\sigma_{\theta 2}|^2 + 2|\sigma_{\theta 1}||\sigma_{\theta 2}|\cos\left(\overrightarrow{\sigma_{\theta 1}}, \overrightarrow{\sigma_{\theta 2}}\right)}; \\ \sigma_{t'} = \sqrt{|\sigma_{t1}|^2 + |\sigma_{t2}|^2 + 2|\sigma_{t1}||\sigma_{t2}|\cos\left(\overrightarrow{\sigma_{t1}}, \overrightarrow{\sigma_{t2}}\right)}. \end{cases} \qquad (15)$$

In a continuously acting blasting, blast wave stresses from both sides have the form $\sigma_{\Theta 1} = \sigma_{\Theta 2} = \sigma_\Theta$, $\sigma_{t1} = \sigma_{t2} = \sigma_t$. Consequently:

$$\begin{cases} \sigma_{\theta'} = \sqrt{2|\sigma_\theta|^2 + 2|\sigma_\theta|^2 \cos\left(\overrightarrow{\sigma_\theta}, \overrightarrow{\sigma_\theta}\right)}; \\ \sigma_{t'} = \sqrt{2|\sigma_t|^2 + 2|\sigma_t|^2 \cos\left(\overrightarrow{\sigma_t}, \overrightarrow{\sigma_t}\right)}. \end{cases} \qquad (16)$$

The blast shock wave propagating to left is taken as an example (Fig. 4).

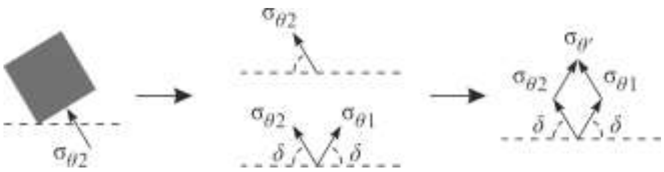

Figure 4. Calculation of stress at superposition of a blast shock wave propagating to the left

The left shock wave forms an incidence angle δ with explosive cavity wall (Fig. 3). The right shock wave forms a similar incidence angle. In addition, it can be concluded that:

$$\cos\left(\overrightarrow{\sigma_{\theta 1}}, \overrightarrow{\sigma_{\theta 2}}\right) = \cos\left(\pi - 2\delta\right) = \cos\alpha \, . \quad (17)$$

Substituting Equation (17) into Equation (16), we obtain dependence between imposed and incident stresses:

$$\begin{cases} \sigma_{\theta'} = \sqrt{2 + 2\cos\alpha \cdot \sigma_\theta}\,; \\ \sigma_{t'} = \sqrt{2 + 2\cos\alpha \cdot \sigma_t}\,, \end{cases} \quad (18)$$

where:

α – is the blast wave main part angle.

Intensities of superimposed and maximum stresses, which are related to blast wave transmission angle, according to experimental data, have the following dependences: $\alpha \approx 60°$, $\sigma_{\theta'} = \sqrt{3\sigma_\theta}$ and $\sigma_{t'} = \sqrt{3\sigma_t}$. Numerical modeling of blast wave interaction is performed by the finite element method using LS-DYNA software. The Lagrange-Euler algorithm is used to reduce the calculation error due to computational grid distortion (which is associated with large deformations and displacements during modeling).

The Jones-Wilkins-Lee equation of state is used to model the dependence between pressure and destruction volume of a solid medium [38]:

$$P = A\left(1 - \frac{\bar{\omega}}{R_1}\right)e^{-R_1 V} + B\left(1 - \frac{\bar{\omega}}{R_2}\right)e^{-R_2 V} + \frac{\bar{\omega}E_0}{V}, \quad (19)$$

where:

P – pressure, Pa;

V – relative volume;

E_0 – initial internal energy density;

R_1, R_2, A, B and $\bar{\omega}$ – defined constants.

In particular: $R_1 = 4.8$, $R_2 = 1.2$, $\bar{\omega} = 0.3$, $A = 405$ GPa, $B = 0.43$ GPa, $P_{CJ} = 11.8$ GPa.

In this study, the impact of counter blast waves on organic glass or polymethyl methacrylate (PMMA) models is simulated. The material characteristics of organic glass plate are: density – $\rho = 2.53$ g/cm^3; shear modulus – $G = 0.304$ GPa; total strength parameter – $A = 0.93$; fracture resistance parameter – $B = 0.088$; fracture strength parameter – $M = 0.35$; strength index – $N = 0.77$; elastic limit – $H_{EL} = 0.0595$ GPa; strain rate – $C = 0.03$; failure criterion – $F_s = 0.8$.

Table 1 shows PMMA dynamic and physical-mechanical characteristics.

Destruction of solid medium (material) as a result of plastic strain accumulation is determined by the Formula [39], [40]:

$$D = \sum \frac{\Delta\varepsilon^p}{\Delta\varepsilon_f^p} \, . \quad (20)$$

Table 1. PMMA dynamic and physical-mechanical characteristics

Parameters	Value
Poisson's ratio	0.31
Modulus of elasticity (GPa)	6.1
Transverse wave velocity (m/s)	1260
Longitudinal wave velocity (m/s)	2320
Optical constant (m^2/N)	$1.08 \cdot 10^{-10}$
Density (kg/m^3)	1230

In Equation (20) are next parameters:

$\Delta\varepsilon^p$ – accumulated plastic deformation during loading;

$\Delta\varepsilon^p_f$ – plastic deformation during destruction under the action of pressure P.

HYPERMESH preprocessing software is used to create the model, partition the grid, develop an algorithm and set the modelling boundary conditions. A triangular grid is used in the calculations, and different detonation points are set according to the coordinates (Fig. 5).

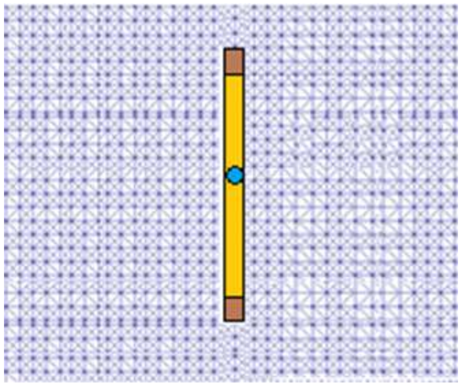

Figure 5. Model schematic and finite element grid fragment with a variable cross-sectional charge initiated from both ends

To study the nature of colliding shock wave propagation in solid media from a directed blasting of an explosive charge with a spherical insert in the center, stress wave generation, propagation and fracturing, tests are conducted using bulk and flat PMMA models (Fig. 5).

PMMA has dynamic characteristics of brittle fracture and the same dynamic characteristics as rock (Table 1) [41]-[43].

Several series of experimental studies are foreseen by the methodology. One part of experiments was conducted using volumetric models with the size of 200×200×150 mm and the other on flat models with the size of 200×200 mm and thickness of 40 mm. For the first series of experiments, an explosive cavity with a diameter of 6-7 mm was drilled in the center of the 200×200×150 mm volumetric model (Fig. 6).

In explosive cavity (Fig. 6), a section of variable cross-sectional charge is formed with a spherical insert placed in the centre. Then, in portions along the column of the explosive cavity, an explosive charge with a mass of 1.0 g of explosive – explosive composition (EC) consisting of PETN + SRF (solid rocket fuel) [44] – is formed with the following calculated and experimental data of its characteristics: detonation velocity $D_{exp} = 4990$ m/s, pressure on explosive cavity walls $P_c = 2.81$ GPa, heat of explosion $Q = 49100$ kJ/kg, density $\rho_{exp} = 995$ kg/m^3. In the mouths of the explosive cavity end parts, warheads are placed, which are switched to the explosive circuit by a non-electric initiation system (NIS) of the ERA type, connected to the detonator and capacitor explosive device (CED) [45].

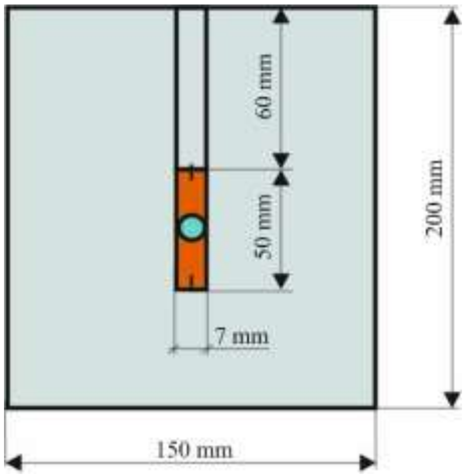

Figure 6. Scheme of experimental model

Figure 7 shows a stand with a high-speed recording system of experiments [46], [47]. Thus, a platform with a testing machine and a model *4* is first placed on a flat horizontal surface of a stand, whose location corresponds to optical line of a passing light beam emitted by a laser *1* of AMPHOS type through a beam expander *2* and a lens *3* for scattering the light beam from one side and a focusing lens 6 in the field of view of the high-speed camera lens *7* of i-SPEED7 type from the other side, which records the process with velocity of 100000 frames per second.

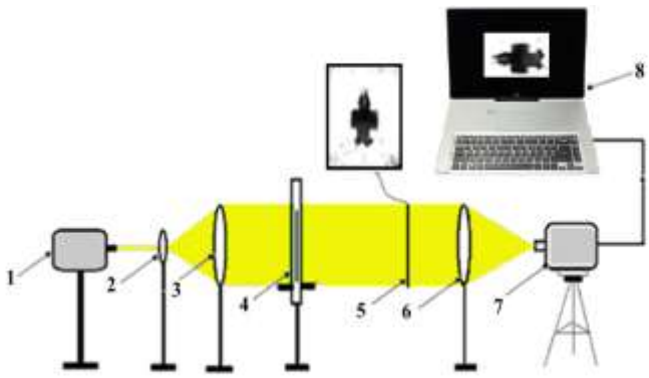

Figure 7. Scheme of experimental stand with high-speed system of experiments registration: 1 – laser; 2 – beam expander; 3, 6 – focusing lenses; 4 – testing machine platform with a model; 5 – process image; 7 – high-speed video camera; 8 – computer

During the experiment, detonator initiates the explosive substance – ten + SRT from both ends, and the light beam emitted by the laser *1*, passing through the light beam expander *2* with its parallel flow passes through the lens *3* and further, falling on the model, the image *5* is obtained. The obtained model loading process image *5* is projected on focusing lens 6 and recorded on speed camera *7*. The recorded information is transmitted to PC, where using software is processed and saved to hard disc.

The second series of experiments studied the character of explosive crack propagation after detonation of explosives in a variable cross-sectional charge from both ends. PMMA is used as a material for the models (Fig. 8). The model is 200 mm long and 200 mm wide and 40 mm thick. The explosive cavity is 100 mm long and 6 mm in diameter.

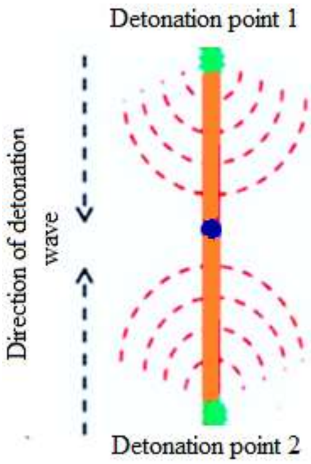

Figure 8. Scheme of experimental model

The explosive used is an explosive composition (EC) consisting of PETN + SRF in a proportion of 80:20%, and two initiation points are installed at both charge ends.

3. Results and discussion

Based on the results of numerical modeling, the distribution of maximum Mises stresses during explosive detonation in a variable cross-sectional charge at both ends has been determined (Fig. 9). The stress field intensity is shown in different colors in the Figure. Before the superimposed shock wave collision, the Mises stress wave form is triangular and propagates mainly along the charge cross-section and in the radial direction. At $t = 10$ μs, the maximum stresses are formed in the center of the explosive cavity together with the shock wave convergence – the inner surface of spherical insert. Stress intensity at the superposition reaches a maximum. At $t = 15$ μs in the superimposed area, the maximum stress with higher intensity is diamond-shaped.

Besides, based on the modeling results, the average values of crack radius of the medium destroyed by blasting of the explosive charge around the explosive cavity have been obtained (Fig. 10).

The numerical modeling results (Fig. 10) are consistent with the experimental results and show that large-scale radial cracks start to form in the central area starting from $t = 12$ μs. A significant crushing zone is observed around the explosive cavity under the effect of high dynamic load from the explosive charge detonation, and cracks start to appear at the explosive cavity face. Due to the high dynamic load caused by superposition (superposition of blast waves in the spherical insert zone), the crack development radius at beginning of superposition is large, which is in accordance with modelling test results. After 24 μs, crack propagation width in the superposition area decreases.

Analysis of experimental results (Fig. 11) shows that large radial cracks are formed on the explosive cavity wall in the superimposed area from both ends of charge detonation, and widths of radial cracks differs. Crack width in high dynamic loading area is approximately 3 times larger than in the weak loading area. This is 11 times the diameter of the explosive cavity and about 5 % longer than its length. Such difference is due to the detonation products superimpose on each other and form a branched fracture zone. The crack width decreases with the weakening of the stress wave caused by the blast action.

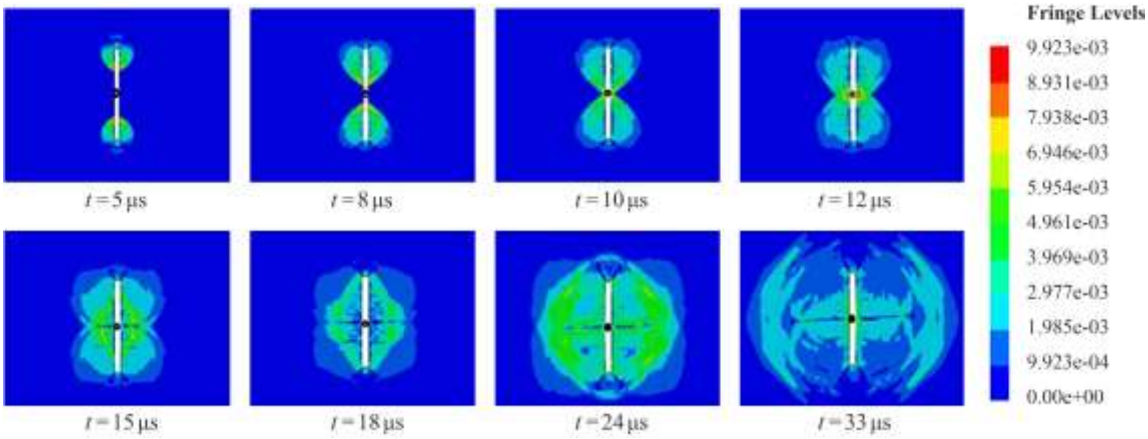

Figure 9. Mises maximum stress formation process

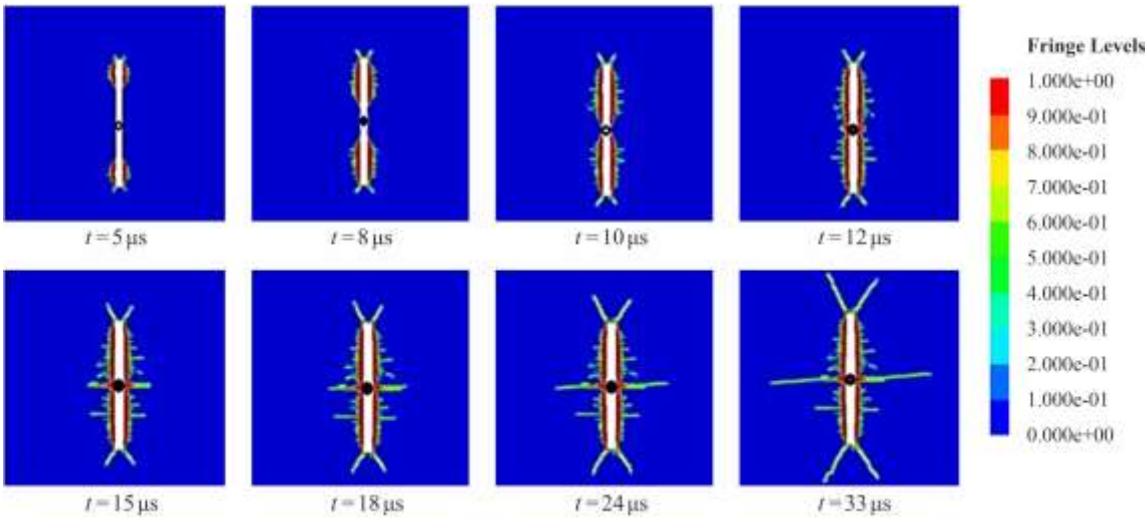

Figure 10. Average value of crack radius at destruction of the medium around explosive cavity

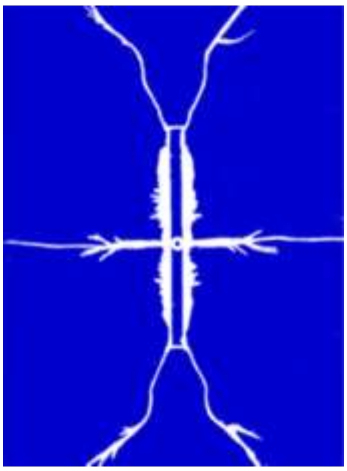

Figure 11. Experimental modelling results on explosion blast crack formation in a variable cross-sectional charge

After detonation at the initiation points, each peak pressure value on the explosive cavity wall increases rapidly and then gradually stabilizes as stress waves propagate. At each detonation point, the pressure on the explosive cavity wall is minimal and 190 MPa is peak pressure. Pressure on the explosive cavity wall is maximal in the charge center, in the zone where the spherical insert is located, with peak pressure amplitude of 540 MPa (Fig. 12).

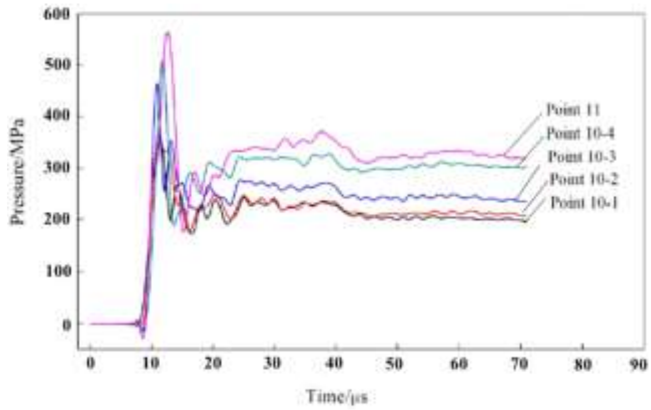

Figure 12. Pressure distribution on the explosive cavity wall near the supposition area

Analysis shows (Fig. 12) that pressure on the explosive cavity wall increases gradually as distance from the measurement point to centre decreases. Superposition area of the explosive cavity wall increases significantly in the range of 5 mm from the centre and amounts to 5% of the total charge length.

According to results of high-speed video recording of model destruction process with an elongated variable cross-sectional explosive charge, initiated from both ends, the kinograms have been made, presented in Figure 13.

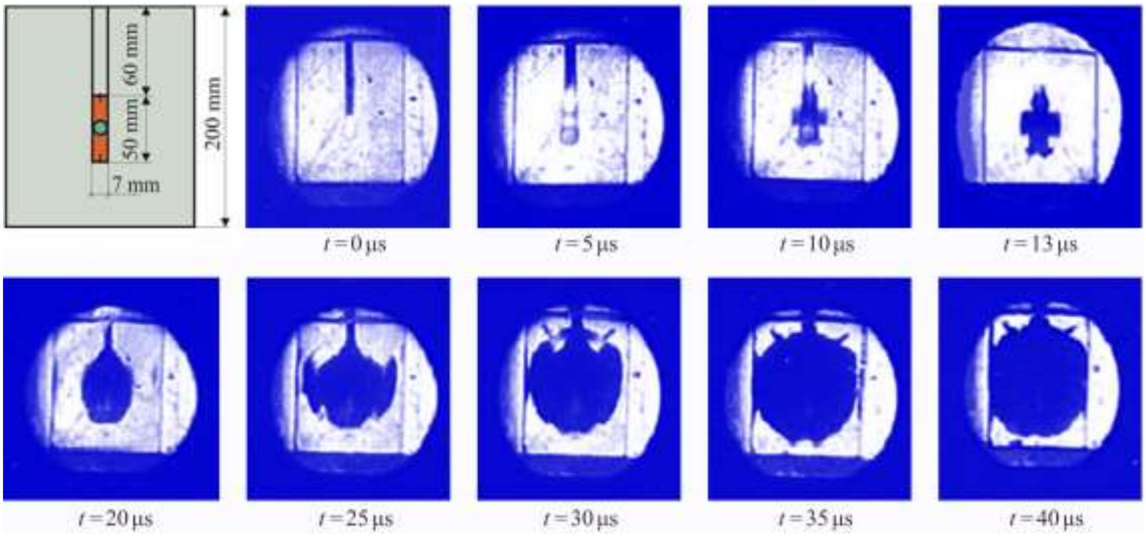

Figure 13. Results of video recording the process of variable cross-sectional explosive charge detonation from both ends of the explosive cavity

After detonation of the explosive composition – PETN + SRF from electric impulse at time t = 5 µs, two groups of shock waves are formed, which propagate with a velocity of 4900 m/s along the charge column towards each other at an angle α relative to the axis of charge, both in radial and axial directions.

After 13 µs, the blast waves from both sides collide in the explosive cavity center in the spherical insert zone, superimpose on each other and focus with increasing intensity. Further, under the influence of focused flow of gaseous detonation products (plasma) on the inner surface of spherical insert, in direction of charge cavity side surface, there is a rupture of its integrity with increase of volume and formation of elliptical-shaped cavity in radial direction (t = 20-25 µs). It has been determined that the velocity of combined shock wave in collision area is higher than that of radial shock wave, which is higher than the axial shock wave velocity. Average value of angles at collision (superposition) of converging blast waves, α, is 60º. After collision and superposition of the blast waves, it takes a pear-shaped form, which persists throughout the expansion process (t = 20-40 µs). Under the action of these loads, the model is completely destroyed. Given research results confirm the operability of proposed construction of an explosive charge of cumulative action for the intensive formation in a destructive medium of a system of directed radial cracks perpendicular to the surface of the charge cavity.

Based on the performed research results of physical and numerical modelling to substantiate the construction of borehole variable cross-sectional charge with cumulative action, the method of its formation has been developed [48], which is implemented in resource-saving and seismically safe method of rock stripping in ore deposit, the scheme of which is shown in Figure 14 [49]. Industrial tests of rational parameters for drilling and blasting operations of the developed method were conducted during large-scale blasts in the production block 1b-1-1t of Inhulska Mine, central deposit of SE VOSTGOK. During the large-scale blast, seismic vibrations of daylight surface at protected objects were measured, which did not exceed safe levels according to National Standard DSTU 4704:2008. "Provedennia promyslovykh vybukhiv. Normy seismichnoi bezpeky" [50] and DSTU 7116:2009 "Vybukhy promyslovi. Metody vyznachennia faktychnoi seismichnoi stiikosti budynkiv i sporud" [51].

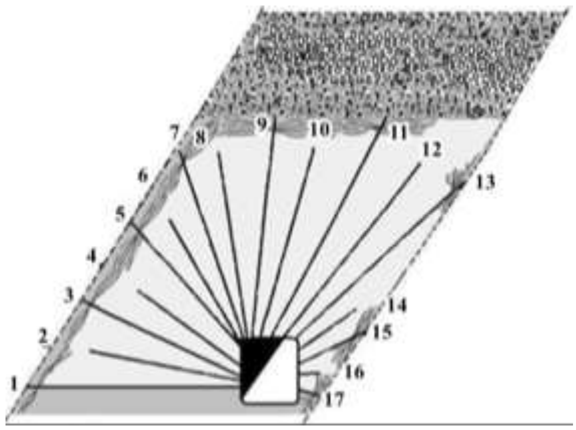

Figure 14. Scheme of hard rock stripping method in the ore deposit production block

The proposed method provides by improving the operation of explosive charges in drill rings to destroy the ore deposit in the block, uniformity in the crushing of hard rocks, a reduction in the ore dilution, seismic safety of blasting operations in areas with developed infrastructure by forming a shielding area in the contact zones of the ore block and backfill mass, and as a consequence, reduction of specific costs of explosive materials, increase the efficiency of explosion, the productivity of crushing-screening and loading-transporting complexes.

4. Conclusions

This paper is aimed to study the interaction between the directed stress fields initiated by the action of explosion in a variable cross-sectional charge at different points of explosive cavity and the efficiency of rock destruction due to the collision of shock waves in the zone of spherical insert location, stress changes on the borehole walls and the nature of crack propagation in the collision (superposition) zone. These studies made it possible to substantiate the efficiency of variable cross-sectional charge of the cumulative action in forming a shielding zone in the ore deposit during its stripping.

It has been determined that the intensity of colliding shock waves from the blast on their surface exceeds the sum of intensities of the superimposed shock wave. At the collision site, kinetic energy is transformed into potential energy with a decrease in velocity at the wave front in its head part and an increase in pressure at its front.

At collision of two shock waves and their focusing in the zone of spherical insert location, the intensity of their impact on the stacks of explosive cavity increases, and cavity expansion from the impact of superimposed shock wave takes a pear-shaped form. It has been found that the shock wave velocity in the collision zone is higher than that the radial shock wave. The average angle of propagation of blast shock waves is about 60º.

A model of stress wave action on the explosive cavity walls in the area of collision (superposition) has been developed. The dependence has been determined between the stress on the explosive cavity walls and the explosive wave propagation angle in the area of collision (superposition). It has been experimentally revealed that the stress on the blast hole walls at the moment of collision (superposition) of blast waves is about 1.73 times higher than the decreasing stress value from a single blast wave.

Model tests and numerical modeling results have shown that large-scale radial fracture cracks are formed on the explosive cavity wall in the area of collision (superposition). The width of the large-scale radial fracture cracks caused by strong dynamic impact is about 5% of the explosive cavity length. The average peak pressure in the area of collision (superposition) of converging explosive cavity shock waves is approximately 1.48 and 1.84 times greater than that in the weakly loaded and unloaded explosive cavity zones.

Performed research results allowed us to substantiate the construction of borehole variable cross-sectional charge with cumulative action, which is implemented in developed resource-saving and seismically safe method of rock stripping in ore deposit. Industrial tests of rational parameters for drilling and blasting operations of the developed method were conducted during large-scale blasts in the production block 1b-1-1t of Inhulska Mine, central deposit of SE VOSTGOK.

Conducted tests have shown that the proposed method provides by improving the operation of explosive charges in drill rings to destroy the ore deposit in the block, uniformity in the crushing of hard rocks, a reduction in the ore dilution, seismic safety of blasting operations in areas with developed infrastructure, and as a consequence, reduction of specific costs of explosive materials, increase the efficiency of explosion, the productivity of crushing-screening and loading-transporting complexes.

Author contributions

Conceptualization: OI, RK, KI; Formal analysis: RK; Funding acquisition: OI, KI; Investigation: OI, LN, IP, VK, RK, KI; Methodology: LN, IP, VK, RK; Project administration: KI; Resources: IP, VK; Software: OI, LN; Supervision: IP, VK, KI; Validation: VK; Visualization: OI, LN, VK; Writing – original draft: LN, IP; Writing – review & editing: OI, RK, KI. 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.

References

[1] Frolov, O.O., Mal'tseva, Yu.S. (2018). Determination of effective diameter downhole charge taking into account the technical and economic assessment blasting works. *Visnyk Kryvorizkoho Natsionalnoho Universytetu*, *46*, 9-14. https://doi.org/10.31721/2306-5451-2018-1-46-9-14

[2] Vovk, O.A. (2013). Parametry seysmicheskikh voln pri deystvii sosredotochennogo zaryada. *Ugol Ukrainy*, *7*, 42-45.

[3] Ishchenko, O., & Ishchenko, B. (2016). Simulation modeling stress field in the vicinity of the stope of orebody. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *3,* 126-130.

[4] Aleksandrova, N.I. (2016). Seismic waves in a three-dimensional block medium. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *472*(2192), 20160111. https://doi.org/10.1098/rspa.2016.0111

[5] Ishchenko, O., Us, S., & Ishchenko, K. (2018). Substantiation of the place of laying of explosive charges in the massif of strong rocks. *The Development of Technical Sciences: Problems and Solutions*, *1*, 13-17.

[6] Ishchenko, O., Us, S., Koba, D., & Ishchenko, K. (2023). Selection and justification of drilling and blasting parameters using genetic algorithms. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *4*, 40-48. https://doi.org/10.33271/nvngu/2023-4/040

[7] Khlevniuk, T.V. (2013). Seismic safety of buildings and structures during blasting operations in quarries. *Visnyk Zhytomyrskoho Derzhavnoho Tekhnolohichnoho Universytetu*, *1*(64), 144-147.

[8] Segarra, P., Sanchidrián, J.A., Castedo, R., López, L.M., & del Castillo, I. (2015). Performance of some coupling methods for blast vibration monitoring. *Journal of Applied Geophysics*, *112*, 129-135. https://doi.org/10.1016/j.jappgeo.2014.11.012

[9] Humenyk, I.L. Strilets, O.P., & Shvets, V.Iu. (2012). Determination of optimal parameters of seismically safe drilling operations at the Pishchansky deposit of migmatites and granites. *Suchasni Resursoenerhosberihaiuchi Tekhnolohii Hirnychoho Vyrobnytstva*, *2*(10), 112-119.

[10] Kumar, R., Choudhury, D., & Bhargava, K. (2016). Determination of blast-induced ground vibration equations for rocks using mechanical and geological properties. *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(3), 341-349. https://doi.org/10.1016/j.jrmge.2015.10.009

[11] Gui, Y.L., Zhao, Z.Y., Jayasinghe, L.B., Zhou, H.Y., Goh, A.T.C., & Tao, M. (2018). Blast wave induced spatial variation of ground vibration considering field geological conditions. *International Journal of Rock Mechanics and Mining Sciences*, *101*, 63-68. https://doi.org/10.1016/j.ijrmms.2017.11.016

[12] Kurinnoy, V.P. (2018). *Theoretical bases of explosive rock destruction*. Dnipro, Ukraine, 280 p.

[13] Li, J.C., Li, N.N., Chai, S.B., & Li, H.B. (2017). Analytical study of ground motion caused by seismic wave propagation across faulted rock masses. *International Journal for Numerical and Analytical Methods in Geomechanics*, *42*(1), 95-109. https://doi.org/10.1002/nag.2716

[14] Zuyevska, N.V., Chala, O.M., Tarasyuk, O.S., & Pasko, M.V. (2018). Modeling of the process of explosive destruction of ferrous quartzites. *Visti*

Donetskoho Hirnychoho Instytutu, *1*, 39-45. https://doi.org/10.31474/1999-981X-2018-1-39-45
[15] Zhukova, N.I. (2014). Development of well charges based on the criterion of energy consumption of drilling rock massifs with voids. *Visnyk NTUU "KPI". Seriia "Hirnytstvo"*, *23*, 40-47.
[16] Leng, Z.D., Sun, J.S., Lu, W.B., Xie, X., Jia, Y., Zhou, G., & Chen, M. (2021). Mechanism of the in-hole detonation wave interactions in dual initiation with electronic detonators in bench blasting operation. *Computers and Geotechnics*, *129*(6), 103873. https://doi.org/10.1016/j.compgeo.2020.103873
[17] Jayasinghe, L.B., Zhou, H.Y., Goh, A.T.C., Zhao, Z.Y., & Gui, Y.L. (2017). Pile response subjected to rock blasting induced ground vibration near soil-rock interface. *Computers and Geotechnics*, *82*, 1-15. https://doi.org/10.1016/j.compgeo.2016.09.015
[18] Dhakal, R.P., & Pan, T.C. (2003). Response characteristics of structures subjected to blasting-induced ground motion. *International Journal of Impact Engineering*, *28*(8), 813-828. https://doi.org/10.1016/S0734-743X(02)00157-4
[19] Babii, K.V., Kratkovsky, I.L., Ishchenko, K.S., & Konoval, V.N. (2019). Innovative resource-saving method of explosive destruction of complex-structural ferruginous quartzites. *Traditions and Innovations of Resource-Saving Technologies in Mineral Mining and Processing*, 44-62.
[20] Zhang, Z.X., Hou, D.F., & Aladejare, A. (2020). Empirical equations between characteristic impedance and mechanical properties of rocks. *Journal of Rock Mechanics and Geotechnical Engineering*, *12*(5), 975. https://doi.org/10.1016/j.jrmge.2020.05.006
[21] Zhang, Z.X. (2014). Effect of double-primer placement on rock fracture and ore recovery. *International Journal of Rock Mechanics and Mining Sciences*, *71*, 208-216. https://doi.org/10.1016/j.ijrmms.2014.03.020
[22] Zhang, Q.B., Zhang, Z.X., Wu, C.S., Yang, J., & Wang, Z. (2022). Characteristics of vibration waves measured in concrete lining of excavated tunnel during blasting in adjacent tunnel. *Coatings*, *12*(7), 954. https://doi.org/10.3390/coatings12070954
[23] Gao, Q., Lu, W., Yan, P., Hu, H., Yang, Z., & Chen, M. (2019). Effect of initiation location on distribution and utilization of explosion energy during rock blasting. *Bulletin of Engineering Geology and the Environment*, *78*(7), 3433-3447. https://doi.org/10.1007/s10064-018-1296-4
[24] Gao, Q., Lu, W., Leng, Z., Yang, Z., Zhang, Y., & Hu, H. (2019). Effect of initiation location within blasthole on blast vibration field and its mechanism. *Shock and Vibration*, *2019*, 5386014. https://doi.org/10.1155/2019/5386014
[25] Miao, Y.S., Li, X.J., Yan, H.H., Wang, X., & Sun, J. (2017). Experimental study of bilinear initiating system based on hard rock pile blasting. *Shock and Vibration*, *2017*, 3638150. https://doi.org/10.1155/2017/3638150
[26] Miao, Y.S., Li, X.J., & Yan, H.H. (2018). Research and application of a symmetric bilinear initiation system in rock blasting. *International Journal of Rock Mechanics and Mining Sciences*, *102*, 52-56. https://doi.org/10.1016/j.ijrmms.2018.01.017
[27] Haeri, H. (2016). Experimental and numerical study on crack propagation in pre-cracked beam specimens under three-point bending. *Journal of Central South University*, *23*(2), 430-439. https://doi.org/10.1007/s11771-016-3088-y
[28] Zhendong, L., Wenbo, L., Ming, C., Yong, F., Peng, Y., & Gaohui, W. (2016). Explosion energy transmission under side initiation and its effect on rock fragmentation. *International Journal of Rock Mechanics and Mining Sciences*, *86*, 245-254. https://doi.org/10.1016/j.ijrmms.2016.04.016
[29] Zhendong, L., Wenbo, L., Ming, C., Fan, Y., Peng, Y., & Gaohui, W. (2019). Explosion energy transmission and rock-breaking effect of in-hole dual initiation. *International Journal of Rock Mechanics and Engineering*, *38*(12), 245-254. https://doi.org/10.1016/j.ijrmms.2016.04.016
[30] Onederra, I.A., Furtney, J.K., Sellers, E., & Verson, S. (2013). Modelling blast induced damage from a fully coupled explosive charge. *International Journal of Rock Mechanics and Mining Sciences*, *58*, 73-84. https://doi.org/10.1016/j.ijrmms.2012.10.004
[31] Liu, L., Chen, M., Lu, W.B., Hu, Y., & Leng, Z. (2015). Effect of the location of the detonation initiation point for bench blasting. *Shock and Vibration*, *2015*, 907310. https://doi.org/10.1155/2015/907310
[32] Zuo, J.J., Yang, R.S., Ma, X.M., Yang, L., & Zhao, Y. (2020). Explosion wave and explosion fracture characteristics of cylindrical charges. *International Journal of Rock Mechanics and Mining Sciences*, *135*(5), 104501. https://doi.org/10.1016/j.ijrmms.2020.104501
[33] Zuo, J.J., Yang, R.S., Gong, M., & Xu, P. (2021). Explosion wave and crack field of an eccentric decoupled charge. *Applied Optics*, *60*(33), 10453-10461. https://doi.org/10.1364/AO.438530
[34] Yang, R.S., & Zuo, J.J. (2019). Experimental study on directional fracture blasting of cutting seam cartridge. *Shock and Vibration*, *2019*, 1085921. https://doi.org/10.1155/2019/1085921
[35] Gerasimov, S.I., & Trepalov, N.A. (2017). Background oriented schlieren method as an optical method to study shock waves. *Technical Physics*, *62*(12), 1799-1804. https://doi.org/10.1134/S1063784217120088
[36] Ding, J.J., Yang, J.H., Ye, Z.W., Leng, Z., Yao, C., & Zhou, C. (2023). Cut-blasting method selection and parameter optimization for rock masses under high in situ stress. *International Journal of Geomechanics*, *23*(12), 04023211. https://doi.org/10.1061/IJGNAI.GMENG-8802
[37] Lin, S.C. (1954). Cylindrical shock waves produced by instantaneous energy release. *Journal of Applied Physics*, *25*(1), 54-57. https://doi.org/10.1063/1.1721520
[38] Wang, Y.B., Wen, Z.J., Liu, G.Q., Wang, J., Bao, Z., Lu, K., Wang, D., & Wang, B. (2020). Explosion propagation and characteristics of rock damage in decoupled charge blasting based on computed tomography scanning. *International Journal of Rock Mechanics and Mining Sciences*, *136*, 104540. https://doi.org/10.1016/j.ijrmms.2020.104540
[39] Dong, T.W., Liu, H.S., Jiang, S.L., Gu, L., Xiao, Q.W., Yu, Z., & Liu, X.F. (2013). Simulation of free surface flow with a revolving moving boundary for screw extrusion using smoothed particle hydrodynamics. *Computer Modeling in Engineering & Sciences*, *95*(5), 369-390. https://doi.org/10.3970/cmes.2013.095.369
[40] Wang, Z.L., Wang, H.C., Wang, J.G., Tian, N.C. (2021). Finite element analyses of constitutive models performance in the simulation of blast-induced rock cracks. *Computers and Geotechnics*, *135*, 104172. https://doi.org/10.1016/j.compgeo.2021.104172
[41] Ayatollahi, M.R., Torabi, A.R., & Firoozabadi, M. (2015). Theoretical and experimental investigation of brittle fracture in V-notched PMMA specimens undercompressive loading. *Engineering Fracture Mechanics*, *135*(6), 187. https://doi.org/10.1016/j.engfracmech.2015.01.005
[42] Zhang, R., Guo, R., & Wang, S.Y. (2014). Mixed mode fracture study of PMMA using digital gradient sensing method. *Engineering Fracture Mechanics*, *119*(2), 164-172. https://doi.org/10.1016/j.engfracmech.2014.02.020
[43] Xu, W., Yao, X.F., Yeh, H.Y., & Jin, G.C. (2005). Fracture investigation of PMMA specimen using coherent gradient sensing (CGS) technology. *Polymer Testing*, *24*(7), 900-908. https://doi.org/10.1016/j.polymertesting.2005.06.005
[44] Efremov, E.I., Ishchenko, K.S., & Nikiforova, V.O. (2014). *Explosive mixture*. Patent No. 88299, Ukraine.
[45] Ishchenko, O.K., & Ishchenko, K.S (2012). *Condenser explosive device*. Patent No. 98546, Ukraine.
[46] Kyrychenko, O.L., Kulivar, V.V., Skobenko, O.V., Khalymendyk, O.V. (2019). A technique to measure V.V. sensitivity of explosives to the effect of laser pulse radiation. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *4*, 11-15. https://doi.org/10.29202/nvngu/2019-4/2
[47] Ishchenko, O.K. (2023). Study on explosion in different cross-sectional shape charge cavity in tensile stress field. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *3*, 32-38. https://doi.org/10.33271/nvngu/2023-3/032
[48] Ishchenko, O.K., Ishchenko, B.S., & Ishchenko, K.S. (2019). *The method of formation of a combined well charge of an explosive substance (ES) of cumulative action*. Patent No. 118458, Ukraine.
[49] Ishchenko, O.K., & Ishchenko, B.S. (2017). *The method of chipping rocks*. Patent No. 118271, Ukraine.
[50] DSTU 4704:2008. (2009). *Provedennia promyslovykh vybukhiv. Normy seismichnoi bezpeky*. Kyiv, Ukraina: Derzhspozhyvstandart.
[51] DSTU 7116:2009. (2010). *Vybukhy promyslovi. Metody vyznachennia faktychnoi seismichnoi stiikosti budynkiv i sporud*. Kyiv, Ukraina: Derzhspozhyvstandart.

Взаємодія вибухових хвиль при детонації вибухової речовини в заряді змінного перерізу

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Мета. Оцінити ефективність та працездатність руйнування твердих середовищ при направленому вибуху вибухової речовини у заряді змінної форми поперечного перерізу.

Методика. Чисельне моделювання процесу взаємодії вибухових хвиль виконано з допомогою методу кінцевих елементом з урахуванням алгоритму Лагранжа-Эйлера. Для встановлення залежностей між тиском та обсягом руйнування середовища використовувалося рівняння стану Джонса-Вілкінса-Лі. Оцінка механізму руйнування твердого середовища при спрямованому вибусі вибухової речовини в заряді зі змінною формою поперечного перерізу оцінювалось з використанням поляризаційно-оптичного методу на моделях з оптично активного матеріалу.

Результати. Експериментальні дослідження руйнування твердого середовища дією спрямованого вибуху вибухової речовини в заряді змінного перерізу дозволили встановити напрямок поширення вибухової хвилі та її амплітуду у хвилі напружень, що впливають на інтенсивність формування мережі радіальних тріщин у місцях їх розповсюдження та спрямованих перпендикулярно до вибухової порожнини. При цьому середній піковий тиск у зоні зіткнення двох ударних хвиль у центрі сферичної порожнини був приблизно в 1.48 та 1.84 рази більший, ніж у слабко навантажених вибуховою хвилею областях. Встановлено, що при зіткненні та накладення двох ударних хвиль інтенсивність їхнього впливу збільшується. Доведено, що швидкість ударної хвилі в зоні зіткнення вища, ніж швидкість ударної радіальної хвилі.

Наукова новизна. Встановлено, що максимальні значення тиску на стінці вибухової порожнини в точках ініціювання різко збільшуються, а потім поступово стабілізуються під час поширення хвиль напружень від вибуху і мають довільний характер розподілу. При цьому слід розглядати три області: не наведені , слабо наведені та сильно наведені. У кожній точці детонації тиск на стінку вибухової порожнини буде мінімальним, а в центрі заряду в зоні сферичної вставки, навпаки, максимальним. При цьому тиск у центральній області суперпозиції приблизно в 2,84 рази більший, ніж на кінцях ініціювання, а характер розподілу змінюється за лінійною залежністю.

Практична значимість. Виконані дослідження можуть бути основою розробки раціональних параметрів ресурсозберігаючих способів відбивання міцних гірських порід складної будови в умовах рудних шахт.

Ключові слова: *вибухова речовина, вибухове навантаження, тверде середовище, заряди вибухової речовини, вибухове руйнування*

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