Mining of Mineral Deposits
Volume 19 (2025), Issue 1, 13-25

https://doi.org/10.33271/mining19.01.013

Influence of a compensatory well diameter on the efficiency of cut cavity shaping in hard rock formations

Oleksii Ishchenko [1], Leonid Novikov [2], Ivan Ponomarenko [3], Volodymyr Konoval [3], Roman Kinasz [4], Kostiantyn Ishchenko [2*]

[1] *Dnipro University of Technology, Dnipro, Ukraine*
[2] *M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*
[3] *Cherkasy State Technological University, Cherkasy, Ukraine*
[4] *AGH University of Science and Technology, Krakow, Poland*

**Corresponding author: e-mail ishenko_k@i.ua*

Abstract

Purpose is to select and substantiate the rational parameters of a compensatory well and its influence on a cut cavity shaping while breaking both stressed and unstressed solid media.

Methods. Numerical simulation of stress field formation under the interaction of blast waves resulting from explosion of a set of holes on a compensatory well has been performed with the help of finite element method as well as ANSYS/LS-DYNA software relying upon MAT_RHT in rock mechanics and MAT_HIGH_EXPLOSIVE in blast mechanics. JWL constitutive equation was applied to define dependencies between the changes in detonation volume and pressure after explosive charges were blasted. A mechanism of the influence of structurally homogeneous solid medium fracture through the explosion of a set of holes on a compensative cavity was assessed on the basis of physical simulation techniques in accordance with the theory of geometric and energy similarity. Stress field in a solid medium was formed applying a photoelastic technique for the models made of the optically active material.

Findings. The experiments aimed at solid medium destruction through explosion have helped understand that after the blasting agent detonation, a blast wave is generated in a well. As the distance increases, the blast wave propagates in rock, and dies down gradually transforming into a stress wave. While achieving compensatory (empty) well, it is reflected from its exposed surface favouring redistribution of stresses and forming the increased stress area in the neighbourhood of its surface. In this regard, the amount of stress concentration around the compensatory (empty) well within the area of the superimposed stress action contributes to rock failure. It has been proved that common effect of the blasting charges with the spherical inserts has demonstrated 2.3 times increase in the amount of the blasted model share to compare with a continuous structure charge, and increase in 50-70% to compare with a charge where diameter of cavity in its frontal part differs from the basic explosion chamber (2-3 d_{hole}).

Originality. It has been identified that the availability of extra free surface (i.e. compensatory cavity) in a cut results in the following: acting on the free surface, explosive stress wave forms a tension wave influences rock near the free surface. Since rock tensile strength is only 1/8-1/15 of compression strength then tensile strength intensity in the reflected wave exceeds the rock strength.

Practical implications. The research may become the basis to develop rational parameters of resource-saving methods for breaking hard rocks differing in complex structure under the conditions of ore mines; mine working driving; and tunneling.

Keywords: *explosive, blasting charges, explosive loading, fragmentation, compensatory well, solid medium*

1. Introduction

Ukrainian mesomorphic rock formation including uranium and iron-ore deposits is widely spread in nature. It occupies almost 66.7% of land area and 77.3% in the countries of Southeast Asia [1]. The horizontally layered rock mass is characterized by transverse isotropy inside which structurally weakened planes are available. The rock formation is of complex nature both in parallel to a structural plane and transversely to the structural plane where soft and hard layers alternate. At the same time, natural state of such a formation is characterized by numerous fractures resulting in its typical anisotropy under the effect of forces and deformations [2]-[5].

Such rocks differ from structurally homogeneous formations in anisotropy of physicomechanical characteristics; availability of both vertical and horizontal joint systems varying in their intensity; and alternation of heavily fissured areas and almost monolithic hard rocks. Structure of the rocks complicates considerably blast energy transition to rock mass to be fragmented under interaction between the extended explosive charges (both blasthole and downhole) as well as the processes controlling intensity of rock blasting

Received: 13 August 2024. Accepted: 20 January 2025. Available online: 30 March 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

fragmentation with the projected seismic effect within the stress-strain formation.

During rock breakage when a propagation distance of a shock wave generated by explosive detonation increases, it transforms rapidly in a stress wave [6] being of crucial importance in the process of rock fragmentation. The availability of natural fissures, stratifications, faults, and other structural peculiarities in the native formations gives rise to changes in their mechanical characteristics; loading conditions; permeability; and nature of energy transfer in the rocks [7]-[9]. Propagation and attenuation of stress waves resulting from explosion inside such rock masses having fissures and faults are also subject to changes due to the structural features; ultimately, the abovementioned influences efficiency and safety of explosive engineering [10]-[12]. Consequently, analysis of the explosively propagating crack as well as the stress waves propagation within a monolithic formation under the effect of a blasting load is quite important to improve the efficiency of explosive energy use; performance capability of rock fragmentation; and safety while constructing underground facilities [13].

In this regard, foreign scientists conducted in-depth research. For example, S. Chai et al. [14] compared propagation nature of stress waves resulting from the explosion in rock mass with transverse and longitudinal fissures using numerical techniques. S. Wang et al. [15] represented Pointing-Thompson model as a discontinuity condition and derived an equation of stress wave propagation through a set of parallel viscoelastic media. It is based upon a recursion method in the time domain to study the influence by viscoelastic compounds (structural defects of a type of filling cement at the block joints, stratification) on stress wave propagation within the formation. However, a discontinuous layer in rock mass influences heavily the stress wave propagation [16]. Hence, it is extremely important to analyze propagation characteristics of a stress wave as well as fragmentation characteristics of hard rock having defects with low performance of filling cement [17].

R.H.C. Wong et al. [18] analyzed propagation process of explosive stress waves, and their interaction with fissures and openings. Moreover, R.H.C. Wong et al. [19] also studied behaviour of fissure propagation in samples having previously formed defects made from various filling materials. It has been defined that the velocity, growth length, and shape of pilot cracks varied in different materials.

H. Lee et al. [20] studied the results of experiments as for the influence on destruction of various defects in rock mass. They have demonstrated that shape, geometry, number, and angle have impact on mechanical characteristics and destruction modes of formation. The results of several studies [21]-[26] show that the number of defects influences heavily mechanical characteristics of rock mass. X.J. Yang et al. [27] have determined impact of defects varying in their shape on the process of fissure origination and propagation. The analysis data shows significant acceleration of fissure propagation if it spreads over near defects (for instance, those being of a circular shape).

B. Xu et al. [28] substantiated the drilling and blasting parameters when a mine working of a large section is driven in a horizontally-layered formation with the developed family of fissures. Relying upon the substantiated drilling and blasting parameters, industrial tests have been performed; moreover, a mechanism of rock breaking in the layered formation has been analyzed. Rational parameters of blasting operations while tunnelling have been optimized as well as the arrangement of blasthole charges along the mine working section, and their maximum length. In the process of the industrial tests, effect by the elongated cylindrical borehole parameters were compared and analyzed. The surrounding rock characteristics, irregularities in the tunnel periphery, and the surrounding rock deformation after explosion were considered as well. While defining the character of adhesion between rock blocks penetrated by fissures, S.M.M. Niktabar et al. [29] applied a test device as for direct shear to analyze the properties of cement engaged in rock cohering. They took into consideration various surface irregularities of the test samples to support the idea that the rock adherence areas are often defenceless against dynamic load resulting from blast action during mineral breaking. The findings show that shear strength of the healed fissures (seams) is higher to compare with the ordinary ones; in addition, shear strength of rock mass decreases along with the increase in the shear period. D.G. Roy et al. [30] and F. Zhang et al. [31] carried out experiments concerning breakage modes of block rock masses differing in viscosity and strength. It has been identified that the fissure (seam) thinning results in the decrease of rock mass viscosity and strength during blasting. The fissured formation area is less sensitive to a crack direction connected with the crack thickness, interaction between the irregular surfaces at the junction intensifies friction resistance, and dissipates energy of the sample breakage.

R.S. Yang et al. [32] analyzed the characteristics of explosively propagating crack growth in rock mass block under high stresses. For the purpose, they used digital caustic laser dynamic system. Based upon the experimental results, crack initiation was obtained involving a stress intensity coefficient and propagation velocity of the crack in the areas of natural defects (i.e. the healed seams). It was concluded that high stress influence intensified significantly a fissure origination within the areas of natural defects (i.e. the healed seams) under shear resulting in the increase of an angle at the crack root. L. Miranda et al. [33] studied the influence of geometry and the number of natural defects (i.e. fissures, and healed seams) on the acoustic wave propagation through the defect loading by means of the acoustic wave. The experiments by D.P. Singh & V.R. Sastry [34] demonstrate that the average blasting parameters are controlled by means of an intersection angle between the structural plane and free surface. Over 0-90° range, an average attenuation (locking) degree of acoustic waves increases along with the increase in the intersection angle.

M. Kucewicz et al. [35] have proposed a procedure to calculate a constitutive KCC model and a new strategy based upon the optimization of rational parameters of brittle fracture. The fracture energy and fracture viscosity were identified experimentally. A comparison of intensity of acceleration as for perturbation formation at the surface of a sample (i.e. formation of surface crusts), the number of radial cracks and their density confirmed the overall repeatability of actual test data.

In the context of papers by such domestic scientists as A.N. Zorin et al. (1978, 2001), E.I. Efremov et al. (1984), V.N. Kharitonov et al. (1982), and A.F. Bulat et al. (1991), SSS of rock mass impact on destructive blast action has been stress-strain state (SSS) determined; the abovementioned is closely connected with mineral mining, and rock breakage at great depths. They influence heavily both energy intensity and nature of explosive rupture of hard rock as well as road-heading indicators as follows: blasthole utilization rate (BUR) decreases; unit costs of explosives and drilling activity increase etc. In this regard, construction cost of underground facilities increases by 1.5-2.0 times; an average increase in prime cost of ore and coal mining is 20%.

An increase in construction of underground facilities as well as mine workings with large cross-section (railroad and subway running tunnel driving; workings in deep mine sinking) needs improvement of the available and development of new resource-saving process solutions; and mineral breakage and treatment involving underground operation cycles. The abovementioned is especially important for complicated mining and geological environments.

The problem solving is intimately connected with the increased blast energy share transformed into breakable rock mass part. Practical application of fresh approaches for hard rock defragmentation being implemented at the expense of new techniques of cut cavity formation (with a compensatory well in the centre of the cut) as well as the design of blastholes, having various shapes of inner surface of an explosion chamber, will help improve rock fragmentation and efficiency of blast operations with the decreased dynamic and seismic impact on buildings (structures), and formation around the charge hole. The techniques are widely used for the directed blasting of buildings (structures) in the process of their demolition [36]; solving complex engineering problems while hard rock breaking (for instance, under development, preparation, and excavation of minerals at deep levels of mines); and construction of various technological facilities under the impact of SSS of rocks [37]. Hence, the factor consideration as for the change in stress state of the environment around explosion chamber at the initial blast stage is the use of such a cut type which will vary character, shape, and direction of a stress field development in a forefield, and improve blasting performance.

Drilling and blasting is still a dominating technique in terms of mining deepening to compare with other methods to drive mine workings; perform tunnelling; and break rocks under the influence by impaction and stress-strain state in the formation [38]. In such a way, formation of a significant amount of a cut cavity as well as extra free surface when impaction may provide new blasting procedures in tunnels (mine workings) [39].

Use of the effect being breakage to additional compensatory cavity is a promising technique improving the efficiency of blasting while tunnelling (mine working driving) at deep levels.

The computer technology progress makes it possible for many scientists and researchers to apply efficient analytical tools for simulation modelling. In particular, those are the methods of finite [40] and discrete elements [41] helping them study a mechanism of blast action in a solid medium within the area of initial static stress operation (for instance, numerical evaluation using a finite-element method for elastic and dynamic problem) through the multiply modelling [42].

To optimize shot-hole parameters, Y. Wang et al. [43] and X. Wu et al. [44] applied a software numerical simulation technique. The results of theoretical calculations performed using ANSYS/LS-DYNA software have shown that use of empty (compensatory) cavities is a cut are of a direct effect as well as stress concentration effect in rock mass in front of a forefield. In such a way, if diameter is 0.051 m of a cavity and distance between loading hole and empty hole is 0.30 m then blasting results are positive. The effect is also confirmed by L. Li et al. [45] and R. Shan et al. [46] through the theoretical analysis and industrial tests.

Use of the proposed mechanism of formation loading has made it possible to identify that explosive detonation favours generation of blast and stress waves with following rock failure. The result of mutual action of three shot holes has helped H. Dan et al. [47] apply two empty wells in the middle of a cut. The blasting technique enables to decrease powder factor; increase operating ratio of shot holes, new surface area, and fragmentation uniformity. J. Gao et al. [48] applied ANSYS/LS-DYNA software to solve numerical modelling problems.

Through numerical modelling, J. Zuo et al. [49] assessed blast effect on the breakable environment with five wells taking into consideration different parameters of a side pressure ratio. Disintegration of the environment has been analyzed if the side pressure ratio varies from explosively propagating crack.

Moreover, the influence by different diameters of cavity wells and block size of the breakable environment on the formation amount of a cut cavity has been studied. Test results have shown that the larger diameter of a compensatory well cavity is the smaller surface of the surface under formation and amount of the broken-up rock mass are. The conclusions have been proposed by X. Zhang et al. [50]. They also established that cavity wells in a cut have both guiding and concentrating effect on rock mass if they are arranged next to each other if a line of least resistance is minimal. The findings have been confirmed by Y. Hao [51] based upon the industrial tests while constructing a deep-level tunnel.

The majority of the abovementioned research results were aimed at the improvement of blasting efficiency and safety within formation; SSS was ignored. Currently, few experiments and numerical modelling are known as for impact of a well diameter in a cut on rock fragmentation involving SSS of a formation.

Hence, it is quite important social and real-world problem requiring effective responses and decisions to develop and implement modern seismic safe drilling and blasting technologies for the faces of mine openings (tunnels) at deep levels of mines within the formation of hard stressed rocks. Application of the developed engineering solutions – new techniques to form a cut cavity – will favour increase in shot-hole use ratio; decrease in unit cost of explosives and amount of drilling operations; construction cost of underground facilities; and prime cost of mining.

2. Methods

Nature of stress field development around shot holes is influenced by the initial intrarock stress field as well as blast dynamic load. The stresses may avoid formation of fissures resulting from blasting operations. Since tangential stress component within formation increases under the action of explosion and peak tension stress decreases [52], area of the broken rock mass becomes smaller. Consequently, a region around the shot hole can be represented under the effect of bound stress field. Within the region, point radial σ_r and tangential σ_θ stresses are described using the Equation system (1):

$$\begin{cases} \sigma_r = \dfrac{1}{2}\left(\sigma_x+\sigma_y\right)\left(1-\dfrac{r_1^2}{r^2}\right)+\dfrac{1}{2}\left(\sigma_x-\sigma_y\right)\left(1-\dfrac{r_1^2}{r^2}\right)\left(1-3\dfrac{r_1^2}{r^2}\right)\cos 2\theta+\rho_c\left(\dfrac{r_1^2}{r}\right)^{\alpha}; \\ \sigma_\theta = \dfrac{1}{2}\left(\sigma_x+\sigma_y\right)\left(1+\dfrac{r_1^2}{r^2}\right)-\dfrac{1}{2}\left(\sigma_x-\sigma_y\right)\left(1+3\dfrac{r_1^2}{r^2}\right)\cos 2\theta-\lambda_d\rho_c\left(\dfrac{r_1}{r}\right)^{\alpha}, \end{cases} \tag{1}$$

where:

σ_x and σ_y – are horizontal and vertical stresses at the point, MPa;

θ – junction of the reference point with a shot hole centre and horizontal direction;

r_1 – the shot hole radius, m;

r – distance between the point and the shot hole centre, m;

α – decay factor during stress wave propagation;

λ_d – side pressure ratio.

After explosive detonates of in a well, a blast wave is generated. As the distance increases, the wave propagates in rock and decays gradually transforming into a stress wave. While achieving compensatory (empty) well and reflecting from its exposed surface, it favours stress redistribution, and shapes high stress area near its surface [53]. Stress concentration [54] around the compensatory (empty) well factors into rock breakage. Field of the superimposed stresses near empty well [55] can be represented through the Equation system (2):

$$\begin{cases} \sigma_{rr} = \dfrac{1}{2}\left[\left(1-k^2\right)\left(\sigma_\theta-\sigma_r\right)+\left(1-4k^2+3k^4\right)\left(\sigma_\theta+\sigma_r\right)\cos 2\theta\right]; \\ \sigma_{\theta\theta} = \dfrac{1}{2}\left[\left(1+k^2\right)\left(\sigma_\theta-\sigma_r\right)+\left(1+3k^2\right)\left(\sigma_\theta+\sigma_r\right)\cos 2\theta\right]; \\ \tau_{r\theta} = \dfrac{1}{2}\left(1+2k^2-3k^4\right)\left(\sigma_\theta+\sigma_r\right)\cos 2\theta; \\ k = \dfrac{r_2}{r_b}, \end{cases} \tag{2}$$

where:

σ_{rr} – radial stress in the reference point after redistribution of the stresses, MPa;

$\sigma_{\theta\theta}$ – tangential stress in the reference point after redistribution of the stresses, MPa;

$\tau_{r\theta}$ – distance between reference point of compensatory cavity centre and shot hole, m;

k – angle between axial line of the shot hole and compensatory cavity;

r_2 – hole well radius, m;

r_b – distance between the nearest point of shot hole and centre of compensatory well, m (Fig. 1).

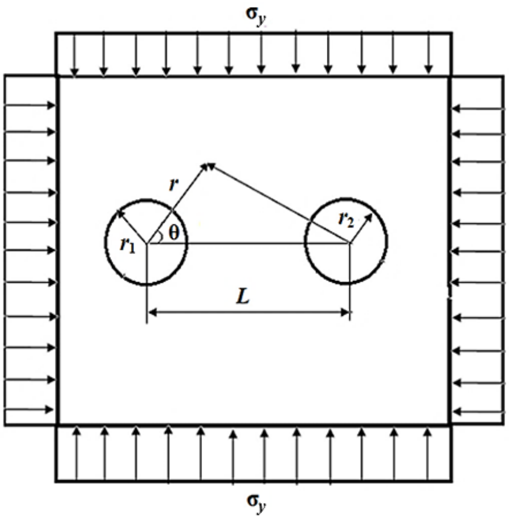


Figure 1. Schematic of stress concentration effect of the empty hole

Hence, the availability of extra free surface (i.e. compensatory hole (cavity)) in a cut results in the fact that acting on the free surface, a blast stress wave forms a tension wave effecting the rock near the free surface. Since the rock tensile strength is only 1/8-1/15 of the compressive strength then tensile stress intensity within the reflected wave exceeds rock strength. In such a way, rock experiences extension and defragmentation at a free surface of the compensatory cavity [56].

A fragmentation grade of a model during the experiments under its explosive loading by means of set of holes in a cut depends upon diameter of a compensatory cavity. The loading results in formation of various stress fields around a compensatory cavity; the abovementioned impacts both blasting performance and fragmentation grade. A model test prevents from direct analysis of stress distribution in the neighbourhood of a compensatory cavity; thus, it is required to analyze stress distribution through numerical modelling techniques, and verification of the results.

A finite-element method with the use of ANSYS/LS-DYNA software was applied to check accuracy of the test results, and their analysis. To implement the program, granite model with 600×600×10 mm was produced. The model is under biaxial confining pressure simulating stress state of solid medium. Characteristics of the granite plate are as follows: density is ρ = 2.6 kg/cm^3; uniaxial compression strength is σ_{stat} = 150 MPa; rock strength coefficient is f = 11-14; longitudinal wave velocity is C_p = 6300 m/s; Young modulus is E = 17.6 MPa; and Poisson ratio is v = 0.25.

The model is blasted by means of four charges placed in the vertices of a square (the total mass is 4 g) inside which compensatory well is located. 100, 60, and 50 mm are its diameters. The model was in an unstressed state and influenced by biaxial confining pressure of high intensity. A finite-difference grid was applied to produce the model and divide it into elements.

Numerical modelling with the use of rock mechanics parameters was performed according to MAT_RHT model; MAT_HIGH_EXPLOSIVE model was applied in terms of blast mechanics [57]. In this context, constitutive equation JWL is applicable to calculate changes in detonation volume and pressure after explosion. Constitutive equation is described with the help of Expression (3):

$$P = A\left(1-\frac{\omega}{R_1V}\right)e^{R_1V} + B\left(1-\frac{\omega}{R_2V}\right)e^{-R_2V} + \frac{\omega E_0}{V}, \quad (3)$$

where:

P – pressure of detonation products, GPa;

V – relative volume of detonation products, m^3;

E_0 – initial density of internal energy, GPa;

A, B, R_1, R_2, and ω – parameters in the constitutive equation.

Table 1 demonstrates the parameters, characteristics, and state of the explosive.

Table 1. Explosive and its constitutive equation parameter

Parameter	Value
Explosive density, ρ, kg/m^3	1100
Detonation velocity, D, m/s	4900
A, GPa	229
B, GPa	0.182
R_1	4.2
R_2	0.9
ω	0.15
Initial density of internal energy E_0, GPa	4.192

To substantiate the rational parameters of drilling and blasting operations for hard rock fragmentation at a great depth while driving mine workings under the conditions of high stress of formation, rather often its breakage characteristics within areas of rock pressure action are ignored. Accordingly, the studies identifying the basic regularities of solid medium breakage under the condition of impaction are of great interest. Their consideration will help develop the rational cut geometry while driving development mine workings at a great depth within hard stress rocks.

According to the developed methods, several series of the experiments using cylindrical models were carried out to substantiate charge designs in a cut with nonenergized compensatory cavities differing in diameter as for their mutual action on breakage of structurally homogeneous solid medium [58].

The sand-cement models were made in the ratio of 1 to one added by 0.5% of water. The sand-cement mixture was hardened by means of portland cement M500. Size of the cylindrical model block was selected based upon a geometric similarity theory [59]. The prepared mixture was poured in a steel cylindrical mold with 240-mm diameter, and 300-mm height. Thickness of the mold wall was 2-3 mm with one free surface; to simulate a solid medium impaction, a holder is mounted on the external surface. Figure 2 shows physical configuration of the model and the experiment scheme.

Then, cut elements are formed in the middle of the model. First, a cylindrical insert is placed to shape compensatory cavities differing in their diameter (i.e. 50, 60, 100 mm), and 180-mm depth. Around it in a R = (0.3-0.35) d_{mod} diameter, explosion chambers – shots with 10-mm diameters are arranged at a depth of 170 mm in the vertices of the inscribed square for explosive charges (Fig. 3).

After the model achieves 30% of hardness, cylindrical inserts were removed from it. Then, they were aged up to the top hardness at room temperature during twenty-eight days. Moreover, to define physicomechanical properties of the model material, cubic form samples with 40 ± 2-mm edge were produced simultaneously for determination of density (ρ); longitudinal wave velocity (C_p); and uniaxial compression strength (σ_{with}) of material of the models in accordance with the current National Standards [60]-[63].

(a)

(b)

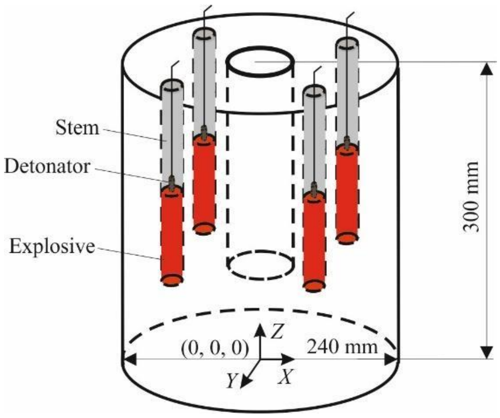


Figure 2. The manufactured models: (a) physical configuration; (b) experiment scheme

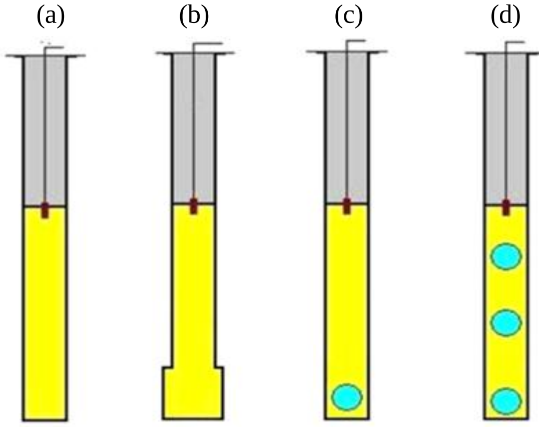


Figure 3. Designs of explosive charges: (a) of a uniform section; (b) with widening in a front face of a shot; (c) with a spherical insert in a front face of a shot; (d) with spherical inserts arranged uniformly columnwise

Charges varying in their design were formed within the prepared cavities of the model (Fig. 3):

– uniform section charge; charge with widening in a front face; charge with a spherical insert in a front face of a hole (shot);

– explosive charge with spherical inserts alternating uniformly columnwise.

Following explosion composition was applied as an explosive: ten + solid rocket propellant [64].

An initiator was placed in the formed charges; mouth was tamped with the help of quartz sand (length was 5-8 shot diameters). After that, the prepared model was mounted in a blasting chamber; charges were commuted into firing circuit with an explosive device [65]; and blasted from a protective shelter.

In the process of the experiment preparation, explosive mass per each shot (well) has been substantiated through trial blasts. In such a way, optimal explosive mass in a shot (well) turned out to be 2.1-2.3 g, and specific consumption was 0.33 kg/m^3. The substantiation has been performed in accordance with energy similarity theory [66].

After explosion, a fragmentation grade of the broken model share was assessed where explosive charge group acted on a compensatory cavity. The broken model share was analyzed in terms of the two factors: nature of the model breakage as a whole; and fragmentation degree of blasting medium reflected from the basic part of the model under mutual action of group of charges on a compensatory cavity.

While processing granulometric composition, the total mass of the blasted model share; amount of fine and coarse fractions; the new formed surface; and medium fragment diameter were determined with the help of a testing screen A30, and set of testing sieves SL-200 #58.

The obtained experimental data are entered in the table formed in MS Excel Application; and processed using the known formulas relying upon papers [67], [68]. Then, cumulative curves of the model share broken by means of explosive charges are plotted. The fact that the explosive charges differ in design and compensatory cavity diameters are 50, 60, and 100 mm is taken into consideration. The results of granulometric analysis of solid medium fragmentation products (models) are applied to calculate their power and granulometric characteristics as follows [69].

The new formed surface of the broken models after their fractioning is determined using the Formula:

$$S_{med} = \frac{6}{\rho} \sum_{i=1}^{n} \frac{m_i}{d_i} - S_0 \,, \tag{4}$$

where:

ρ – density of the models (g/cm^3);

m_i and d_i – mass (g) and diameter (cm) of average fragment of i^{th} fraction respectively;

S_0 – initial area of the model surface (cm^2).

The medium fragment diameter is calculated through the Formula:

$$d_{med} = \sum_{i=1}^{i} w_i d_i \,, \tag{5}$$

where:

$w_i = m_i / m$ – number of i^{th} fraction or i^{th} fragment, unit fractions;

m_i – i^{th} fraction mass, g;

m – total mass of all fractions, g;

d_i – medium size of i^{th} fraction or i^{th} fragment, cm.

Energy intensity of the new surface unit formation is characterized by a specific surface energy value (γ). Consequently, breakage of solid media (models) by means of explosive charge blast where mass is M, and explosion heat is Q (kJ/kg) which power is applied to make the new surface unit being γ_n, can be represented as follows:

$$\gamma_n = \frac{MQ}{S_{nb}} \,, \tag{6}$$

where:

S_{nb} – new formed surface resulted from explosion, cm^2;

M – high-order explosive (ten) mass $150 \cdot 10^{-6}$ kg;

Q – explosive (ten) heat $5908 \cdot 10^3$ J/kg.

Fragmentation degree of solid media (models) is identified with the help of the Formula:

$$K_f = \frac{h_{med}}{d_{med}} \,, \tag{7}$$

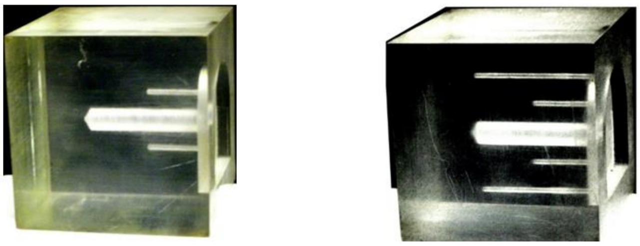
where:

h_{med} – averaged size of the model edge, cm; and

d_{med} – medium fragment diameter.

The mechanism to form a cut cavity under the model loading with sets of explosive charges on a compensatory cavity in the cut as well as the process of stress wave formation and propagation in addition to cracking nature were analyzed using 3-D plexiglass (polymethylmethacrylate – PMMA) models (Fig. 4).

(a)



(b)

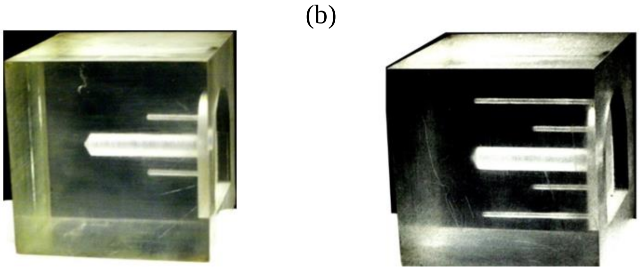


Figure 4. Physical form of the 3-D models with set of shots in a cut involving compensatory well: (a) short shots; (b) long and short shots

PMMA has dynamic characteristics of brittle failure; its dynamic characteristics are comparable with dynamic characteristics of rock (Table 2) [70]-[72]. The material characteristics of the plexiglass 3-D model are as follows: density is ρ = 2.53 kg/cm^3; shear modulus is G = 0.304 GPa; complete strength parameter is A = 0.93; crack resistance parameter is B = 0.088; failure parameter is M = 0.35; strength index is N = 0.77; elastic strength is H_{el} = 0.0595 GPa; strain rate is C = 0.03; and failure criterion is F_s = 0.8.

Table 2 demonstrates dynamic and physicomechanical characteristics of plexiglass.

Table 2. Dynamic and physicomechanical characteristics of PMMA

Parameters	Value
Poisson ratio	0.31
Elasticity modulus, GPa	6.1
Transversal 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

The methods have involved several series of the experiments using 3-D models which geometry is 150×150×150 mm. The experiments were carried out by means of a model on one edge of which a mine working profile is formed and compensatory well with 15-20-mm diameter and 75-mm length is drilled in the central part. Around the compensatory well, shots of prismatic walking cut are bored with 5-6-mm diameter, and differing in length. Within the drilled explosive cavities (shots) shaping the cut cavity periphery, variable cross-section charges were arranged with the spherical inserts in the centre of the charge. Diameters of the charges are 0.5 d_{char} and (0.8-0.9) d_{char}, where d_{char} is the charge diameter. As for short shots, continuous structure was applied with the use of explosive composition consisting of ten + solid rocket propellant mixture [64], which mass is 200 mg. Its design and experimental data are as follows: detonation velocity is D_{expl} = 4990 m/s; pressure on an explosive chamber walls is P_c = 2.81 GPa; explosion heat is Q = 49100 kJ/kg; and density is ρ_{expl} = 995 kg/m^3.

The initiators being a bridge with joint hinge of lead azide (mass is 10 mg) were placed in the explosive cavity mouths (shots). Through a conductor chain, they commuted with a blasting circuit coupled to explosive condenser device [65]. The mouth was tamped with the help of quartz sand (length was 5-8 shot diameters).

The prepared charges, which scheme was described above, were connected in the series into a chain with time delaying between the charge groups and an explosive tool synchronized with the laser action and high-speed chamber; after that, they were blasted. The experiments were carried out using high-velocity system for test recording [73], [74].

In such a way, a platform having an even horizontal surface which was prepared in the lab is used for erection of a test facility involving simulation machine TECNOTEST (Italy) and the model. It was placed in such a way to help optical line of the transmitted light beam radiated by a laser of AMPHOS type through a beam-expanding device and lens for beam scattering pass through its middle from one side, and the focused lens in vision of high-speed camera lens of *i*-SPEED type from another side which records the process with velocity being up to 1000000 frames a second.

In the course of the experiment, the initiator blasts an explosive composition consisting of ten + solid rocket propellant mixture; in turn, light beam emitted by a laser passes through the beam extender. Hence, by means of its proper parallel flow, the light beam penetrates the lens and achieves the model. In such a way, its image is obtained. The image of model loading is projected on a focusing lens and recorded by the high-speed camera. The recorded data is transmitted to a PC to be processed and accumulated by magnetic media with the help of software.

3. Results and discussion

Relying upon the numerical modelling through finite-element methods and using MAT_RHT model in rock mechanics and MAT_HIGH_EXPLOSIVE in blast mechanics, changes in detonation volume and pressure after explosive charge firing were calculated in accordance with constitutive equation JWL (Fig. 5).

It has been determined that a stress wave after blast in explosive cavities along a cut cavity formation propagates through concentric circles up to the model boundaries. In the neighbourhood of a compensatory well, stress redistribution area is formed where in 40 μs stress wave achieves a wall reflecting from it repeatedly, and tension wave shaping. In this context, stress wave range is concentrated mainly in a shot hole; failure is near a compensatory well. By t = 220 μs time, stress wave is attenuated gradually and the test block breaks down shaping a cavity as a result of shot set explosion.

While analyzing the process of model breakage on compensatory wells with 50-mm and 60-mm diameter (Fig. 5a, b) it is possible to draw a conclusion on the yield of coarser fractions and lesser stress value. In this regard, a wave reflected from a compensatory cavity, redistributes with compression stress formation within the area; and tension stresses decay by t = 220 μs time. Hence, the sample cannot be broken down. Only in 220 μs, a stress wave dissipates gradually and the test block experiences its complete breakage shaping a cut cavity. The research is in good agreement with findings concerning fragmentation efficiency of solid media through explosion. Figure 6 shows a diagram of change in a stress field within the model for different time moments.

A comparative analysis of a diagram in the area of stress field formation (Fig. 6) where axial static pressure is available (Fig. 6a) and is not available (Fig. 6b) demonstrates that if there is no retaining pressure stress propagates faster over the model. Moreover, diagram area in the stress field is larger for such loading types and efforts by explosive pressure in the neighbourhood of shots (wells) favours increase in tension stress if retaining pressure is not available. If retaining pressure takes place, it inhibits the explosive wave propagation and deteriorates the efficiency of solid medium fragmentation.

Explosion composition consisting of ten + solid rocket propellant mixture was placed in the prepared explosion chambers [64]. The total explosive mass in the charges was 4 g; and the specific explosive consumption was 0.33 kg/m^3.

In the process of the charge fabrication, the explosion mixture was put in paper cylinders (cartridges) where continuous structure charges with a section varying in height were formed. External cartridge diameter was 0.95 of a charge cavity diameter; internal diameter was 0.92. Variable section charges were formed through sprung widening within the charge cavity edge; arrangement of hollow spheres within the charge cavity edge; and uniform arrangement along the charge column (Fig. 3).

The prepared models were erected in a metal box (i.e. explosive cavity) and blasted remotely from a protective shelter by means of an explosive condenser device [65]. The experiments were carried out at the test site of granite quarry.

After explosion, a fragmentation grade of the model share broken-down by means of explosive charge group on a compensatory cavity was evaluated. While processing the granulometric composition, the total mass of the blasted model share; the number of fine and coarse fractions; the new formed surface; and a middle fragment diameter were determined. The middle fragment diameter as well as the new formed surface was identified using the known formulas relying upon papers [67], [68]. Table 3 demonstrates the processing results concerning the experimental data.

The research analysis has shown that a continuous design charge explosion as well as a charge with a sprung widening at its edge formed radial crack system; however, no significant increase in the broken down model share is determined.

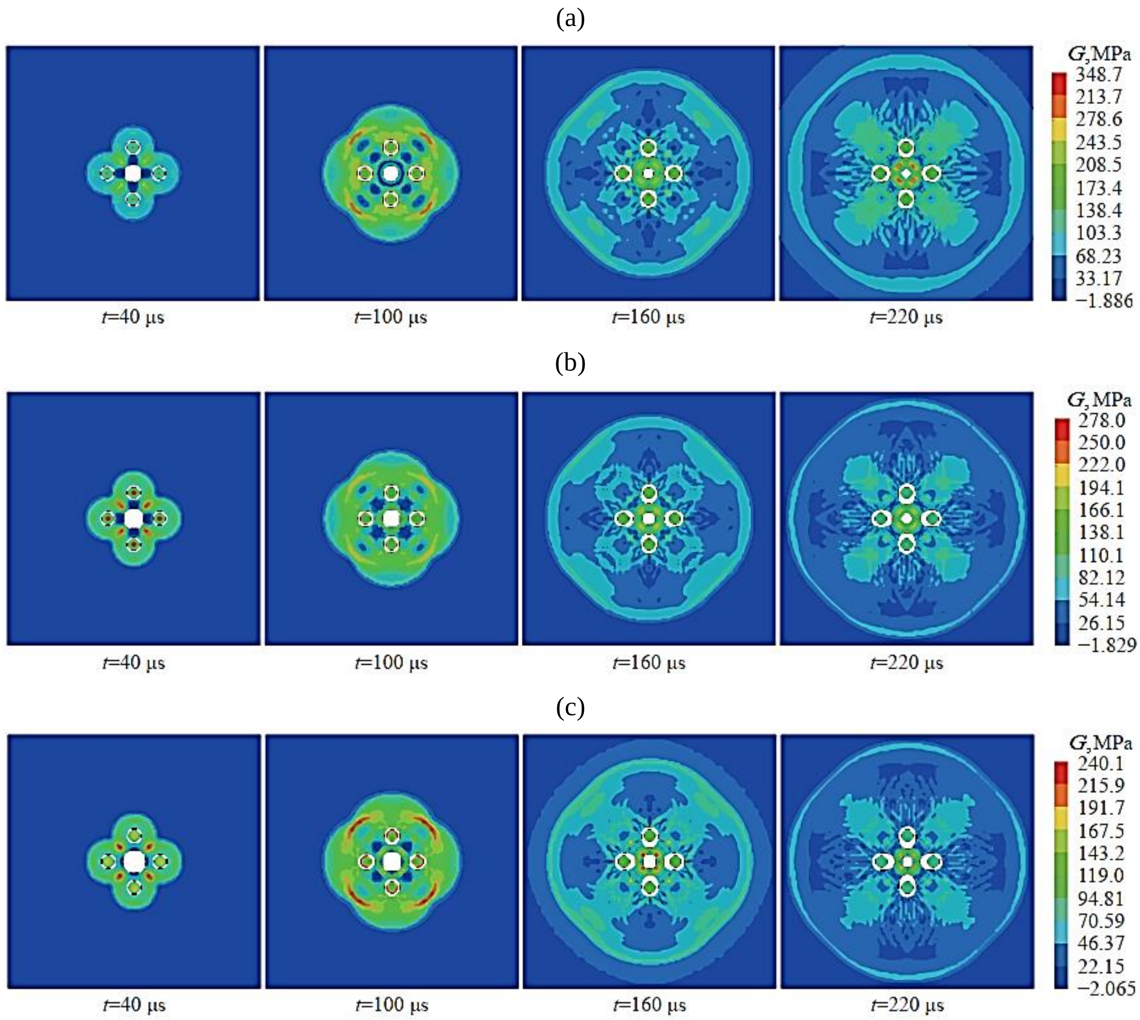


Figure 5. Diagram of the stress field distribution resulting from explosion of a set of boreholes on a compensatory well with a diameter of: (a) being 50 mm; (b) being 60 mm; (c) being 100 mm

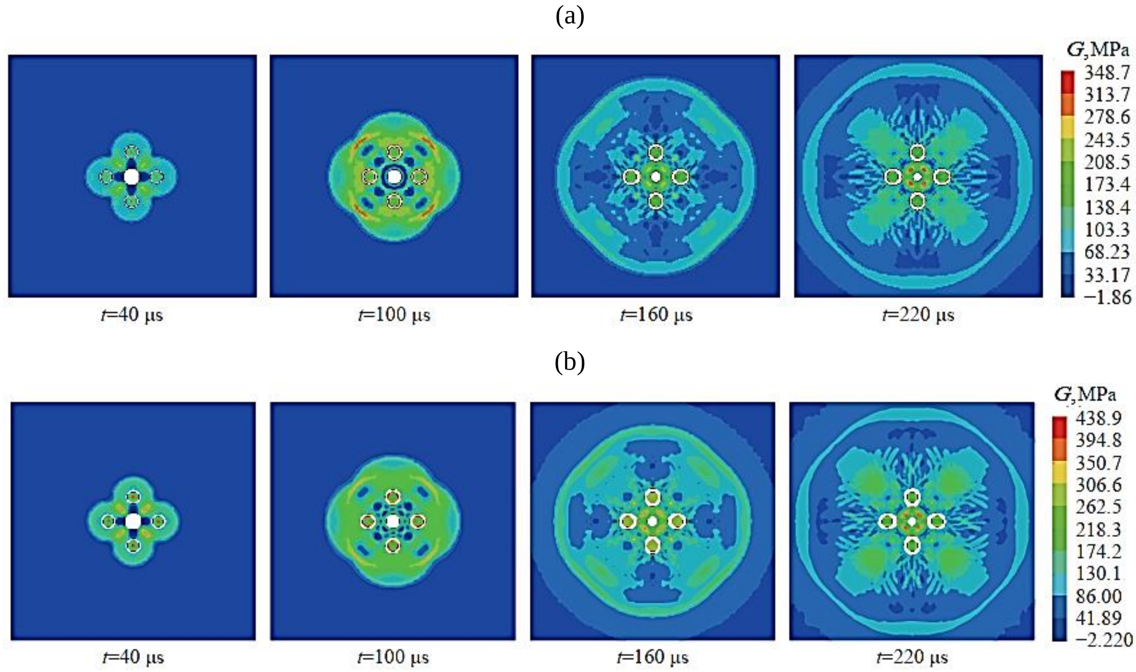


Figure 6. Diagram of the change in the stress field in the model from the explosion of a set of boreholes on a compensatory well with a diameter of 60 mm over time: (a) being under the action of a retaining axial pressure; (b) being without any action of a retaining axial pressure

Table 3. The results of sand-cement models breakage using explosives differing in their design on a compensatory cavity

Charge designs	Mass of the blasted model share, m, kg	Middle fragment diameter d_{aver}, mm	Fraction percentage of the blasted model, %		Volume of the blasted model, $V \cdot 10^{-3}$, m^3	Area of the new shaped surface, S_n, cm^2
			d_i < 20 mm	d_i > 50 mm		
Compensatory cavity diameter d_{cc} = 100 mm						
Uniform section charge	1.397	15.65	57.7	28.1	0.726	66.0
Charge with a spherical insert at a shot edge	3.965	33.53	34.2	34.4	2.06	101.7
Charge with uniform columnwise arrangement of spherical inserts	2.825	37.7	32.8	39.2	1.50	123.0
Charge with a sprung widening at its edge	2.325	27.9	38.4	20.6	1.20	68.3
Compensatory cavity diameter d_{cc} = 60 mm						
Uniform section charge	2.450	42.7	27.5	51.4	1.27	137.5
Charge with a spherical insert at a shot edge	3.360	32.4	43.0	36.8	1.74	101.8
Charge with uniform columnwise arrangement of spherical inserts	3.804	30.2	44.5	39.2	2.0	89.1
Charge with a sprung widening at its edge	2.905	47.0	15.45	60.0	1.5	163.0
Compensatory cavity diameter d_{cc} = 50 mm						
Uniform section charge	2.569	36.4	32.0	41.6	1.33	117.7
Charge with a spherical insert at a shot edge	3.965	33.53	34.2	34.4	2.06	85.7
Charge with uniform columnwise arrangement of spherical inserts	3.176	30.3	39.2	29.2	1.65	89.0
Charge with a sprung widening at its edge	2.777	48.8	16.8	63.3	1.44	166.7

As for the models broken down using explosives where charges have spherical inserts at their edge and being arranged uniformly columnwise, radial crack system has been formed in their locations; the cracks are directed deep into the model. Moreover, the areas have been defined with the melted inserts in the form of pellets of a model blasted using variable section explosive charge.

It has been identified that after the blasted model share was removed and sized, a surface in the form of the flattened cone was shaped at the level of a boundary depth of the compensatory cavity (130-180 mm). Small base of the cone is equal to the compensatory cavity diameter (i.e. 100 mm) and lateral surface of the undisturbed model share took the shape of an ellipse. In addition, it has been demonstrated that mutual action of explosive charges with spherical inserts results in 2.3 times increase of the blasted model part amount to compare with a continuous structure charge. Moreover, it is by 50-70% more than a charge having an explosion chamber at its edge which diameter differs from the basic explosion chamber (i.e. 2-3 d_{hole}).

The analysis of model breakage results has shown that the middle fragment diameter while blasting the models by means of continuous structure charges is 15.65 mm. If a charge with spherical inserts at its edge was applied then the diameter is 33.53 mm; if inserts are distributed columnwise then the diameter was 37.7 mm; and if the charge has explosion chamber at its edge differing from the basic explosion chamber then the diameter is 27.9 mm. It should be mentioned (Table 3) that the new shaped surface resulting from a model share blasting by means of a variable section charge is 1.5 times more to compare with a charge where a part of an explosion chamber has a diameter differing from the basic one.

The films were produced on the results of fast video recording of fragmentation of models with different sets of shot explosion charges in a cut having a compensatory cavity (i.e. of a continuous structure; and with a variable section (Fig. 7).

For each of the experimental series, the prepared charges of such an explosion composition (i.e. ten + solid rocket propellant) were in connected in a sequential chain and blasted with a delay action. As images (Fig. 7a, b) explain, the first frames of the process recording, within 0-16 μs interval after initiating pulses are fed and delay of groups of the charges being short and long, detonation front is formed at their surface (transparent field within the frames). At a speed of 4900 m/s, the front moves along an explosive charge column to a shot edge with radial crack system propagation around the explosion cavity and forms pear-shaped breakage crater. Then, within 40-140-μs interval, the film frames (Fig. 7a) show action by gaseous detonation products as for destruction of space between shots and compensatory well with its widening and fracturing zone forming with following increase in amount (Fig. 7a, b).

Further analysis of the explosive charges blasts in a cut (long shots are of a variable section and short ones are of a continuous structure) has demonstrated mutual interaction of charge groups blasted with delay relative to short and long shots (Fig. 7b; film frames 24-40 μs). Then, consideration of a model breakage process (Fig. 7b; film frames 40-64 μs) has made it possible to understand that placement of a spherical insert at the edges of long shots favours more active propagation of radial cracks, and their penetration by gaseous detonation products. In such a way, formation process of a cut cavity as well as following efficient breakage of a solid medium results in the increased amount of outburst crater (Fig. 7b; film frames 64-88 μs).

The analysis of the frames shows that within arrangement areas of spherical inserts where the formed cumulative gas flow is focused and moved towards an explosion chamber edge within following redistribution and concentration of non-uniform and non-stationary stress field in the places favours its strength degradation and efficient fragmentation since the stress field exceeds the solid medium strength.

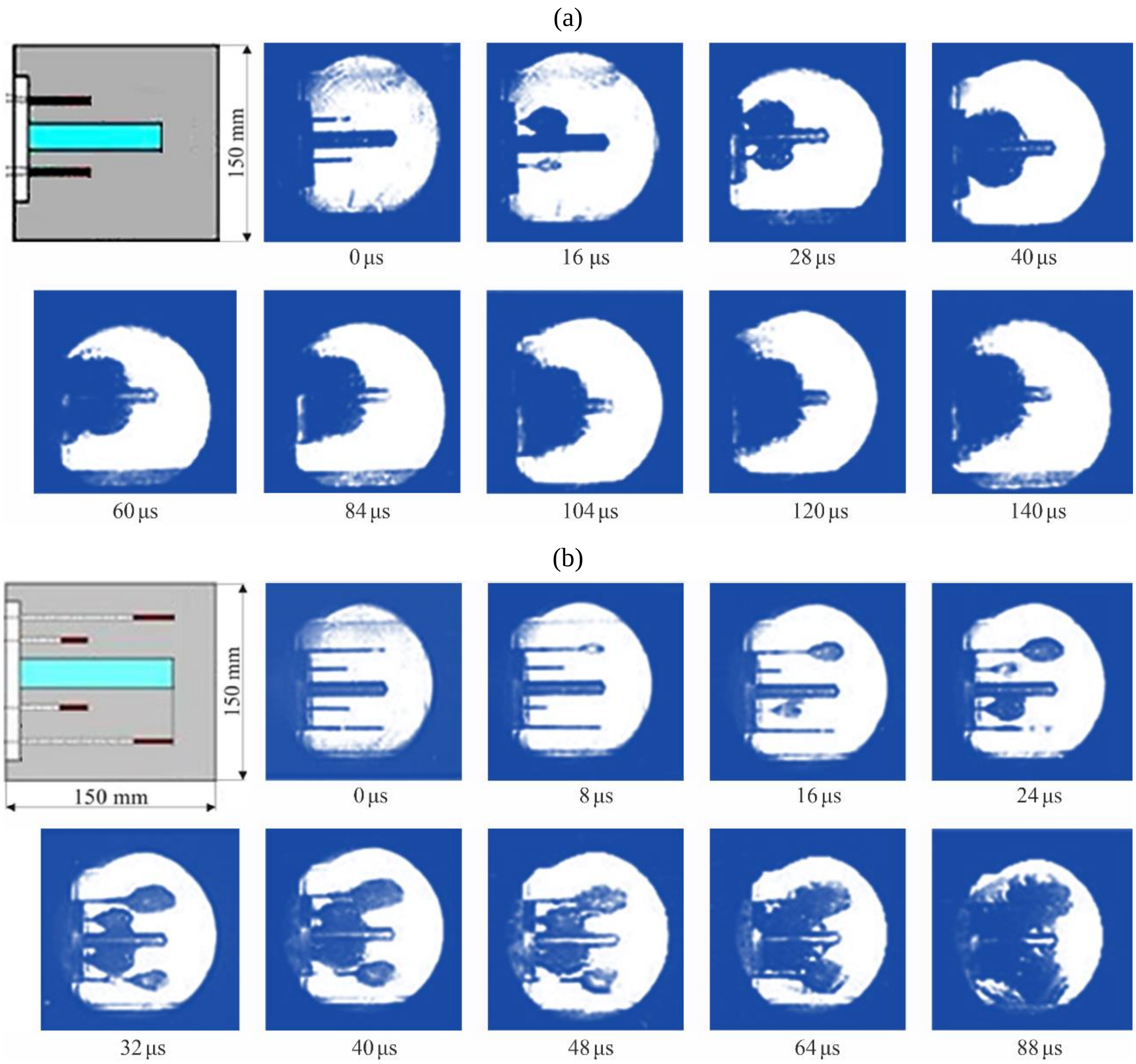


Figure 7. Films of fragmentation of models differing in shot sets in a cut on a compensatory cavity: (a) of a continuous structure; (b) with a variable section

In accordance with the performed physical and numerical modelling, rational parameters have been substantiated for the development of sectional moving cut with a compensatory well in its central share. Use of such a cut (and it various modifications) blasting patterns were generated to drive workings (two railway tunnels are meant: two-track Beskyd entry in the Carpathians, and running tubes for subway in Dnipro) at deep levels of coal and ore mines where cross section is 9 to 40 m^2 and more [75].

Industrial tests of the rational parameters of drilling and blasting operations of the proposed technique to form a cut cavity help: decrease the yield of oversize fragments at the expense of the improved operation of explosive charges on a compensatory well; obtain a uniform fragmentation of hard rock; reduce the unit cost of explosive materials as well as drilling; and improve the detonation efficiency as well as crushing and grading complexes, and loading and transporting facilities.

4. Conclusions

The research studies the formation and interaction of stress fields initiated by explosion action of sets of charges differing in their cross-section on a compensatory well. It also assesses the mechanism and breakage efficiency of solid medium on compensatory wells of different diameters at the expense of expansion of stress distribution zone at the surface of a compensatory well; changes in peak stress values on an explosion chamber walls; and nature of crack propagation within the areas where detonating waves interact. The analysis has helped substantiate the basic parameters of three-level moving cut with the non-charged compensatory well in its central part.

A model of stress wave effect on an explosion chamber walls has been developed as well as the influence of compensatory well diameters on stress concentration arising near openings. In this regard, the effect by the reflected tension waves impacts the efficiency of blast energy as for medium breakage in the neighbourhood a compensatory well and increases in the peak values of a stress wave and their range near the opening. In turn, the compression and tension stresses near empty opening and a shot hole are compared with the stresses under compressive axial pressure. Such an effect makes it possible to arrive at both selection and substantiation of rational diameter of a compensatory well in a cut.

The results of simulating tests and numerical modelling have made it possible to analyze a blast action mechanism while breaking structurally a homogeneous solid medium under impaction conditions. For the purpose, long explosive charges varying in their structure were applied in a cut with compensatory cavity. They also have shown that while continuous construction charge blasting as well as a charge with sprung widening at a shot edge, radial crack system was shaped. Nevertheless, no significant increase in the broken-down model share was observed. In turn, in the context of models blasted by means of explosive charges with spherical insert at a shot edge and arranged uniformly columnwise, system of radial cracks directed deep into the model has been shaped in the areas of the placement.

It has been identified that in the process of model breakage using continuous structure charge, a middle fragment diameter was 15.65 mm. If charges with spherical inserts at a charge edge were applied, the diameter was 33.55 mm; columnwise distributed charges showed 37.7-mm; and if a charge diameter at the edge of an explosion chamber differed from the basic cavity then it was 27.9 mm.

The research has been carried out to study a mechanism of a cut cavity formation using continuous structure explosive charges as well as a variable section throughout its height. Models made of optically active materials were applied.

It has been defined that within the areas where spherical inserts are placed and where cumulative gas flow is focused and moves towards a charge cavity with its following impact on the medium under breakage, a non-uniform and non-stationary stress field is concentrated; the stress field exceeds the medium strength favouring its weakening as well as efficient fragmentation.

The research results have helped develop and substantiate new blasting patterns as for a cut cavity formation while underground facility construction within the hard rock masses. The fresh procedures of rock breakage were tested under the conditions of the SE VostokGOK; and while constricting railway and running tunnels for subway in Dnipro. It has been identified that 15-% increase in shot use ratio (0.95-0.97) decreases specific costs for drilling operations by 10%; and specific cost for explosives. Moreover, a grade (uniformity) of rock fragmentation was improved as well.

Author contributions

Conceptualization: OI, RK, KI; Formal analysis: RK; Funding acquisition: OI, KI; Investigation: OI, LN, IP, VK, RK, KI; Methodology: LN, IP, 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.

Funding

Research was conducted according to complex program of the National Academy of Sciences of Ukraine on the nuclear energy development “Development of scientific bases and improvement of methods and means of increasing the efficiency and safety of mining operations in uranium ore mining” (No. GR 0117U004231) and the agreement on scientific-technical cooperation between M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro University of Technology, Cherkasy State Technological University and AGH University of Science and Technology.

Acknowledgements

We thank the colleagues from the National Academy of Sciences of Ukraine for their support. We also acknowledge the contributions of researchers from M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, University of Technology, Cherkasy State Technological University and AGH University of Science and Technology, Poland.

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] Bo, W. (2016). *Study on disturbance zone evolution and anchoring mechanism of surrounding rock in layered rock tunnel*. Wuhan, China: China University of Geosciences.

[2] Lisjak, A., Grasselli, G., & Vietor, T. (2014). Continuum-discontinuum analysis of failure mechanisms around unsupported circular excavations in anisotropic clay shales. *International Journal of Rock Mechanics and Mining Sciences*, *65*(19), 96-115. https://doi.org/10.1016/j.ijrmms.2013.10.006

[3] Han, Z., Qiao, C., & Xu, H. (2017). Analysis of strength anisotropy of rock mass with a set of persistent joints. *Journal of China University of Mining & Technology*, *46*(5), 1073-1083.

[4] Yang, Z., Gao, Y., & Wu, S. (2018). Study of the influence of joint parameters on rock mass strength based on equivalent rock mass technology. *Journal of China University of Mining & Technology*, *47*(5), 979-986.

[5] Cheng, J., Yang, S., & Yin, P. (2018). Experimental study of the deformation and strength behavior of composite rock specimens in unloading confining pressure test. *Journal of China University of Mining & Technology*, *47*(6), 1233-1242.

[6] Dai, J. (2002). *Dynamic characteristics of rock and blasting theory*. Beijing, China: Metallurgical Industry Press.

[7] Xia, W., Lu, W., & Chen, M. (2019). Study on safety threshold of peak particle velocity about blasting damage of columnar jointed basalt rock mass in Baihetan Dam site. *Chinese Journal of Rock Mechanics and Engineering*, *38*(S1), 2997-3007.

[8] Varma, M., Maji, V.B., & Boominathan, A. (2021). Influence of rock joints on longitudinal wave velocity using experimental and numerical techniques. *International Journal of Rock Mechanics and Mining Sciences*, *141*, 104699. https://doi.org/10.1016/j.ijrmms.2021.104699

[9] Wang, Z.L., & Konietzky, H. (2009). Modelling of blast-induced fractures in jointed rock masses. *Engineering Fracture Mechanics*, *76*(12), 1945-1955. https://doi.org/10.1016/j.engfracmech.2009.05.004

[10] Yang, P., Lei, Q., Xiang, J., Latham, J.-P., & Pain, C. (2020). Numerical simulation of blasting in confined fractured rocks using an immersed-body fluid-solid interaction model. *Tunnelling and Underground Space Technology*, *98*, 103352. https://doi.org/10.1016/j.tust.2020.103352

[11] Wang, Z., Wang, H., Wang, J., & Tian, N. (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

[12] Zhu, J.B., Zhao, X.B., Li, J.C., Zhao, G.F., & Zhao, J. (2011). Normally incident wave propagation across a joint set with the virtual wave. *Journal of Applied Geophysics*, *73*(3), 283-288. https://doi.org/10.1016/j.jappgeo.2011.01.012

[13] Do, T.N., & Wu, J.H. (2020). Verifying discontinuous deformation analysis simulations of the jointed rock mass behavior of shallow twin mountain tunnels. *International Journal of Rock Mechanics and Mining Sciences*, *130*, 104322. https://doi.org/10.1016/j.ijrmms.2020.104322

[14] Chai, S., Li, J., & Zhao, J. (2019). Study on stress P-wave propagation across intersecting rock joints with nonlinear deformation. *Chinese Journal of Rock Mechanics and Engineering*, *38*(6), 1149-1157. https://doi.org/10.13722/j.cnki.jrme.2018.1085

[15] Wang, S., Wang, Z., & Jia, S. (2022). Analysis of propagation characteristics of stress waves in viscoelastic jointed rock mass. *Journal of Harbin Institute of Technology*, *54*(2), 99-107. https://doi.org/10.11918/202010035

[16] Zhao, H., Yu, H., Yuan, Y., & Zhu, H. (2015). Blast mitigation effect of the foamed cement-base sacrificial cladding for tunnel structures. *Construction and Building Materials*, *94*, 710-718. https://doi.org/10.1016/j.conbuildmat.2015.07.076

[17] Zhao, F., Shi, Z., Yu, S., & Zheng, H. (2023). A review of fracture mechanic behaviors of rocks containing various defects. *Underground Space*, *12*, 102-115. https://doi.org/10.1016/j.undsp.2023.02.006

[18] Wong, R.H.C., Chau, K.T., Tang, C.A., & Lin, P. (2001). Analysis of crack coalescence in rock-like materials containing three flaws – Part I: Experimental approach. *International Journal of Rock Mechanics and Mining Sciences*, *38*(7), 909-924. https://doi.org/10.1016/S1365-1609(01)00064-8

[19] Wong, R.H.C., Tang, C.A., Chau, K.T., & Lin, P. (2002). Splitting failure in brittle rocks containing pre-existing flaws under uniaxial compression. *Engineering Fracture Mechanics*, *69*(17), 1853-1871. https://doi.org/10.1016/S0013-7944(02)00065-6

[20] Lee, H., & Jeon, S. (2011). An experimental and numerical study of fracture coalescence in pre–cracked specimens under uniaxial compression. *International Journal of Solids and Structures*, *48*(6), 979-999. https://doi.org/10.1016/j.ijsolstr.2010.12.001

[21] Wang, L., Zhu, Z., Zhou, L., Gao, W., Dong, Y., Niu, C., & Ai, T. (2021). Study the effect of circular hole on dynamic fracture properties of cracked PMMA specimen under impact loads. *International Journal of Impact Engineering*, *156*, 103948. https://doi.org/10.1016/j.ijimpeng.2021.103948

[22] Wang, H., Zhu, Z., Zhou, L., Gao, W., Dong, Y., Niu, C., & Ai, T. (2022). Fracturing behavior of brittle solids containing 3D internal crack of different depths under ultrasonic fracturing. *International Journal of Mining Science and Technology*, *32*(6), 1245-1257. https://doi.org/10.1016/j.ijmst.2022.09.008

[23] Wang, H., Li, H., Tang, L., Ren, X., Meng, Q., & Zhu, C. (2022). Fracture of two three-dimensional parallel internal cracks in brittle solid under ultrasonic fracturing. *Journal of Rock Mechanics and Geotechnical Engineering*, *14*(3), 757-769. https://doi.org/10.1016/j.jrmge.2021.11.002

[24] Manouchehrian, A., & Kulatilake, P.H.S.W. (2022). Numerical study on rock failure around a tunnel destressed by a conceptualized notched technique. *Underground Space*, *7*(6), 1086-1097. https://doi.org/10.1016/j.undsp.2022.02.003

[25] Fang, K., Tang, H., Li, C., Su, X., An, P., & Sun, S. (2023). Centrifuge modelling of landslides and landslide hazard mitigation: A review. *Geoscience Frontiers*, *14*(1), 101493. https://doi.org/10.1016/j.gsf.2022.101493

[26] Zhang, F., Yang, L., Man, D., Liu, N., Wei, P., Sui, Z., & Liu, Y. (2024). Explosive stress wave propagation and fracture characteristics of rock-like materials with weak filling defects. *Engineering Fracture Mechanics*, *308*, 110372. https://doi.org/10.1016/j.engfracmech.2024.110372

[27] Yang, X.J., Ming, W., Gong, W., Pan, Y., He, M., & Tao, Z. (2023). Support characteristics of flexible negative Poisson's ratio anchor cable response to blasting impacts. *Underground Space*, *8*, 162-180. https://doi.org/10.1016/j.undsp.2022.04.010

[28] Xu, B., Zhang, W., & Shi, W., (2019) Experimental study of parameters of tunneling blasting in jointed layered rock mass. *Journal of China University of Mining & Technology*, *48*(06), 1248-1255.

[29] Niktabar, S.M.M., Rao, K.S., & Shrivastava, A.K. (2017). Effect of rock joint roughness on its cyclic shear behavior. *Journal of Rock Mechanics and Geotechnical Engineering*, *9*(6), 1071-1084. https://doi.org/10.1016/j.jrmge.2017.09.001

[30] Roy, D.G., Singh, T.N., & Kodikara, J. (2017). Influence of joint anisotropy on the fracturing behavior of a sedimentary rock. *Engineering Geology*, *228*, 224-237. https://doi.org/10.1016/j.enggeo.2017.08.016

[31] Fei, Z., Yang, L., Man, D., Liu, N., Wei, P., Sui, Z., & Liu, Y. (2024). Explosive stress wave propagation and fracture characteristics of rock-like materials with weak filling defects. *Engineering Fracture Mechanics*, *308*, 110372. https://doi.org/10.1016/j.engfracmech.2024.110372

[32] Yang, R., Ding, C., Yang, L., & Chen, C. (2018). Model experiment on dynamic behavior of jointed rock mass under blasting at high-stress conditions. *Tunnelling and Underground Space Technology*, *74*, 145-152. https://doi.org/10.1016/j.tust.2018.01.017

[33] Miranda, L., Cantini, L., Guedes, J., Binda, L., & Costa, A. (2013). Applications of sonic tests to masonry elements: influence of joints on the propagation velocity of elastic waves. *Journal of Materials in Civil Engineering*, *25*(6), 667-682. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000547

[34] Singh, D.P., & Sastry, V.R. (1987). Role of weakness planes in bench blasting – A critical study. *Processing of the 2nd International Symposium on Rock Fragment by Blasting*.

[35] Kucewicz, M., Baranowski, P., Gieleta, R., & Małachowski, J. (2022). Investigation of dolomite' rock brittle fracture using fully calibrated Karagozian Case Concrete model. *International Journal of Mechanical Sciences*, *221*, 107197. https://doi.org/10.1016/j.ijmecsci.2022.107197

[36] Song, G., Zhong, M., Wang, M., Long, Y., Liu, Y., Xu, J. (2018). Collapse process and impact effect of viaduct demolition based on centrifugal model. *Soil Dynamics and Earthquake Engineering*, *115*, 246-251. https://doi.org/10.1016/j.soildyn.2018.07.034

[37] Nesterova, Y.S. (2017). Experience of destressing slotting to prevent gasdynamic events in mechanized carnallite mining. *Journal of Mining Science*, *53*(2), 291-298. https://doi.org/10.1134/S106273911702214X

[38] Renshu, Y., Zhaoran, Z., & An, C. (2020). Discussion on ultra-deep depth problem of slot hole in blasting excavation of rock roadway in coal mine. *Coal Science and Technology*, *48*(1), 10-23. https://doi.org/10.13199/j.cnki.cst.2020.01.002

[39] Li, G., Lei, N., & Li, W. (2018). Study on rapid excavation technology for hard rock roadway in coal mine. *Coal Science and Technology*, *46*(11), 13-20.

[40] Lisjak, A., Figi, D., & Grasselli, G. (2014). Fracture development around deep underground excavations: Insights from FDEM modelling. *Journal of Rock Mechanics and Geotechnical Engineering*, *6*(6), 493-505. https://doi.org/10.1016/j.jrmge.2014.09.003

[41] Vazaios, I., Vlachopoulos, N., Diederichs, M.S. (2019). Assessing fracturing mechanisms and evolution of excavation damaged zone of tunnels in interlocked rock masses at high stresses using a finitediscrete element approach. *Journal of Rock Mechanics and Geotechnical Engineering*, *11*(4), 701-722. https://doi.org/10.1016/j.jrmge.2019.02.004

[42] Milner, D., Wesevich, J., Nikodym, L., Nasri, V., Lawver, D., & Mould, J. (2018). Improved blast capacity of pre-engineered metal buildings using coupled CFD and FEA modeling. *Journal of Loss Prevention in the Process Industries*, *56*, 486-497. https://doi.org/10.1016/j.jlp.2018.10.008

[43] Wang, Y., Shi, X., & Wang, F. (2021). Optimization of blasting parameters of burn cut in underground mine. *Mining and Metallurgical Engineering*, *41*(5), 36-40. https://doi.org/10.3969/j.issn.0253-6099.2021.05.009

[44] Wu, X., Jia, J., Wang, L., Zhou, S., Wu, H., Zhao, X., & Gong, M. (2024). Easer hole design method based on the principle of minimum burden at the hole bottom and its application in tunnel blasting. *Processes*, *12*(8), 581. https://doi.org/10.3390/pr12081581

[45] Li, L., Zhang, D., & Yao, J. (2015). Experimental study on large diameter cutting with empty hole in underground phosphate ore. *China Mining Magazine*, *24*(11), 139-141.

[46] Shan, R., Zhou, J., & Huang, B. (2010). Analysis on slotting blasting influencing factors of mine roadway. *Coal Science and Technology*, *38*(2), 25-27.

[47] Dan, H., He, C., Yaoyao, Z., Chang, W., & Yingjun, Z. (2019). Research on high efficiency blasting technology of broken rock mass in underground bauxite. *China Mining Magazine*, *28*(9), 116-119. https://doi.org/10.12075/j.issn.1004-4051.2019.09.007

[48] Gao, J., Xie, S., Zhang, X., Wang, H., Gao, W., & Zhou, H. (2020). Study on the 2D optimization simulation of complex five-hole cutting blasting under dif-ferent lateral pressure coefficients. *Complexity*, *11*, 1-12. https://doi.org/10.1155/2020/4639518

[49] Zuo, J., Yang, R., & Xiao, C. (2018). Model test of empty hole cut blasting in coal mine rock drivage. *Journal of Mining Science and Technology*, *3*(4), 335-341.

[50] Zhang, X., Li, J., Li, D., Xie, S., Zhou, H., & Li, T. (2021). Numerical simulation of parallel cutting with different number of empty holes. *Tehnički Vjesnik*, *28*(5), 1742-1748. https://doi.org/10.17559/TV-20201211121650

[51] Hao, Y. (2021). Application of large diameter hollow hole in rock tunneling. *Mining Technology*, *21*(1), 21-23.

[52] Huang, X., Qiang, J., & Zhang, X. (2022). Numerical simulation research on rock breaking mechanism of four-hole cut blasting underground stress. *Journal of Shandong University of Science and Technology (Natural Science)*, *41*(2), 60-69.

[53] Zhang, X., & Chen, S. (2002). Study on blasting fragmentation prediction of jointed and fractured rock mass considering impact. *Chinese Journal of Rock Mechanics and Engineering*, *8*, 1141-1146.

[54] Fan, J., Zhang, Z., & Zu, J. (2020). Experimental study on parallel cut blasting effect of large diameter emptyhole. *Safety in Coal Mines*, *51*(5), 83-87. https://doi.org/10.13347/j.cnki.mkaq.2020.05.016

[55] Lv, Y., Yuan, C., Fu, Y., Zhu, X., Gan, Q., Li, H., & Chen, Q. (2022). Empty-hole effect on fracture propagation under blasting load. *Arabian Journal of Geosciences*, *15*(8), 765. https://doi.org/10.1007/s12517-022-09967-7

[56] Zhaoran, Z., Huayi, C., Weigang, J., & Tianfu, Y. (2020). Rock breaking mechanism and blasting parameters of straighthole cutting with empty-hole. *Journal of China Coal Society*, *45*(S2), 791-800. https://doi.org/10.13225/j.cnki.jccs.2019.1591

[57] Cai, Y., & Fu, H. (2017). Experimental study on hydraulic blasting stress wave propagation and coal broken mechanism. *Journal of China Coal Society*, *42*(4), 902-907. https://doi.org/10.13225/j.cnki.jccs.2016.1239

[58] Zuevska, N.V., Ishchenko, K.S., Ishchenko, O.K., & Korobiychuk, V.V. (2021). *Geomechanics of explosive destruction of solid rock massifs during the construction of underground facilities*. Kyiv, Ukraine: Igor Sikorsky Kyiv Polytechnic Institute, 392 p.

[59] Komir, V.M., Geiman, L.M., Kravtsov, V.S., & Myachina, N.I. (1972). *Modeling the destructive effect of an explosion in rocks*. Moscow, Russia: Nauka, 214 p.

[60] GOST 21153.0-75. (1975). *Rocks. Sampling and general requirements forthe methods of physical testing*.

[61] GOST 12730.0-2020. (2020). *Concretes. General requirements for methods of determination of density, moisture content, water absorptions porosity and water tightness*.

[62] GOST 21153.2-84. (1984). *Rocks. Method for determining the ultimate strength in uniaxial compression*.

[63] GOST 21153.7-75. (1975). *Rocks. Method for determining velocities of propagation of elastic longitudinal and transverse waves*.

[64] Efremov, E.I., Ishchenko, K.S., & Nikiforova, V.O. (2014). *Explosive mixture*. Patent No. 88299, Ukraine.

[65] Ishchenko, O.K., & Ishchenko, K.S. (2012). *Condenser explosive device*. Patent No. 98546, Ukraine.

[66] Yufei, Z. (2018). *Model test study on confining pressure effect of cut blasting in high geo-stress rock lane*. Beijing, China: China University of Mining and Technology.

[67] Ishchenko, O.K., & Ishchenko, K.S. (2018). *Method for modeling explosive rock destruction*. Patent No. 116911, Ukraine.

[68] Ishchenko, K.S. (2014). *Method for modeling explosive rock destruction*. Patent No. 104707, Ukraine.

[69] Ishchenko, K.S., Konoval, S.V., Saveliev, D.V., Kratkovsky, I.L., & Krukovskaya, V.V. (2014). *A method for estimating the energy intensity of the destruction of anisotropic rocks under different types of loading on models*. Patent No. 95218, Ukraine.

[70] Ayatollahi, M.R., Torabi, A.R., & Firoozabadi, M. (2015). Theoretical and experimental investigation of brittle fracture in V-notched PMMA specimens under compressive loading. *Engineering Fracture Mechanics*, *135*(6), 187. https://doi.org/10.1016/j.engfracmech.2015.01.005

[71] 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

[72] 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

[73] Kyrychenko, O.L., Kulivar, V.V., Skobenko, O.V., & Khalymendyk, O.V. (2019). A technique to measure 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

[74] 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

[75] Ishchenko, O.K., & Strilets, O.P. (2023). Efficiency and seismic safety of constructing underground structures in complex rock masses. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *6*, 67-72. https://doi.org/10.33271/nvngu/2023-6/067

Вплив діаметра компенсаційної свердловини на ефективність формування врубової порожнини в масиві міцних гірських порід

О. Іщенко, Л. Новіков, І. Пономаренко, В. Коновал, Р. Кінаш, К. Іщенко

Мета. Вибір і обґрунтування раціональних параметрів компенсаційної свердловини та її вплив на ефективність формування врубової порожнини при руйнуванні напружених і ненапружених твердих середовищ.

Методика. Чисельне моделювання процесу формування поля напружень при взаємодії вибухових хвиль від вибуху комплекту шпурів на компенсаційну свердловину виконано за допомогою методу скінченних елементів та програми розрахунку ANSYS/LS-DYNA згідно моделі MAT_RHT у механіці гірських порід, а в механіці вибуху – MAT_HIGH_EXPLOSIVE. Для встановлення залежностей між зміною обсягу та тиску детонації після вибуху зарядів вибухової речовини використовувалося рівняння стану JWL. Оцінка механізму руйнування структурно однорідного твердого середовища вибухом комплекту шпурових зарядів на компенсаційну порожнину проводилася на базі методів фізичного моделювання згідно з теорією геометричної та енергетичної подібності, а формування поля напружень у твердому середовищі – поляризаційно-оптичного методу на моделях з оптично активного матеріалу.

Результати. Експериментальними дослідженнями руйнування твердого середовища вибухом встановлено, що після детонації вибухової речовини в свердловині генерується ударна хвиля, яка в міру збільшення відстані поширюється в породі і поступово згасає, переходячи в хвилю напружень, досягаючи компенсаційної (порожньої) свердловини, відбиваючись від її відслоненої поверхні, що сприяє формуванню області підвищеного напруження поблизу її поверхні. Причому величина концентрації напружень навколо компенсаційної (порожньої) свердловини в зоні дії перерозподілу полів напружень сприяє руйнуванню породи. Доведено, що при спільній роботі зарядів вибухової речовини зі сферичними вставками зафіксовано збільшення у 2.3 рази об'єму відбитої вибухом частини моделі порівняно із зарядом суцільної конструкції та на 50-70% із зарядом, що має у торцевій частині вибухову порожнину діаметром, відмінним від основної вибухової порожнини (2-3 $d_{шп}$).

Наукова новизна. Встановлено, що присутність у додатковій вільній поверхні компенсаційної порожнини призводить до того, що вибухова хвиля напружень, впливаючи на вільну поверхню, утворює хвилю розтягу, яка діє на породу біля вільної поверхні. А оскільки міцність гірських порід на розтяг становить всього 1/8 до 1/15 міцності на стиск, то інтенсивність напружень розтягу у хвилі відбивання є більшим межі міцності породи.

Практична значимість. Виконані дослідження можуть бути основою для розробки раціональних параметрів ресурсозберігаючих способів відбивання міцних гірських порід складної будови в умовах рудних шахт, під час проведення гірничих виробок та будівництва тунелів.

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

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers.