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Physical and simulation modelling of solid media fracturing by means of explosive charges of different cross-sectional shapes

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Abstract

Purpose is to evaluate experimentally and theoretically a mechanism of solid media fracturing by means of explosive charges varying in their cross-sectional shapes.

Methods. The Mohr-Coulomb strength condition has been applied to describe rock transition to the disturbed state. The condition has become a basis to develop a mathematical model of explosion (i.e. shock and detonation wave) of the concentrated borehole charges. The simulation explosion was modelled while adequate load applying at the points belonging to the outline of both cylindrical charge and at the charging angles in the shapes of triangular and square prisms. The evaluation mechanism of solid media fracturing by means of explosive charges, varying in their shapes, used the models made of optically active materials. A method of high-speed photorecording of the process was involved; the method was combined with the photoelastic technique of stress analysis.

Findings. Taking into consideration rock transition to the disturbed state, the Mohr-Coulomb strength condition was applied with the possibility to simulate failures resulting from shear as well as from separation according to the developed mathematical model. The calculation results have helped identify distribution of a geomechanical parameter (Q) at different time points (time iterations). Dependencies of changes in the maximum component of the main stress tensor $\sigma_1 / \gamma H$ along the axis passing through the charge centres perpendicularly to its flat surface for different time iterations have been developed. It has been defined that the maximal stresses are concentrated on the top of both triangular and square prisms helping shape a denser crack network within the zones.

Originality. It has been identified that at the initial explosion stage, the maximum values of the main stress tensor component $\sigma_1 / \gamma \mathrm{H}$ along the axis passing through the charge centre perpendicularly to its flat surface, experience certain change depending upon a power law with the increasing distance to the charge outline. At the same time, if the charge is of a square prism shape then time iteration being $i = 5$ makes the main stress decrease according to a linear dependence.

Practical implications. The research may be used as the basis for the development of rational parameters of the resource-saving methods applied to separate hard complex rocks in terms of open pits where building materials are mined.

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

1. Introduction

There are significant reserves of both explored and industrially developed deposits of ore and non-metallic minerals in Ukraine concentrated within the metasomatic and metamorphic solid rock mass of the Ukrainian Shield. The rocks are of complex structure; hence, their separation should involve extra measures for their effective fracture. The measures are associated with the improvement of the available and development of new effective resource-saving techniques and fracturing methods, their following processing, mechanization of production processes using high-tech equipment and modern explosives, and quality planning and organization of the activities in open pits. It follows from the abovementioned that control of the specific explosive energy value while complex hard rock breaking-down is possible owing to different methods. Among other things, it can be achieved through certain changes in the area of direct borehole explosive charge-breakable rock contact or through the created conditions reducing the dynamic impact of the explosion on the charge cavity surface [1]-[3]. The problems can be solved owing to adequate selection and substantiation of the explosive charge design. According to a geometric principle, the explosive charge design can be divided into two main groups: elongated charges of constant and variable diameter in its height and the ones with different configurations, both in the length and cross-section [4]-[8].

Efficient control of the explosion impact should involve the fact that rock tensile and shear strength is almost 10 times less than the rock compressive one. As far as energy intensity of solid media fracturing is proportional to the square of their

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ultimate strength under a particular loading type, the energy intensity of their fracture by means of tensile forces is 100 times less than the energy intensity under compressive stresses. Consequently, the charges with variable diameters have clearly expressed maxima and minima of energy potential on their height; hence, the explosion efficiency of such charges is achieved at the expense of suppressing role of tensile stresses. Therefore, the improvement of borehole charge design is one of the main ways to increase explosion efficiency and conditions of explosion energy transfer to rock mass. In such a way, use of elongated charges of variable diameters and different cross-sectional shapes helps reduce prime cost of explosive fracture of complex rocks in open pits where ore and non-metallic minerals are mined.

Adequate selection of a borehole charge design to improve efficiency of explosive fracturing of solid rocks with complicated structure has become a basis for the development and industrial mastering of the known method for rock blasting using borehole charges of variable diameters along a bench height taking into consideration the energy approach to calculate the charge parameters [9]. Paper [10] shows that continuous borehole charge with constant cross-section substitution for a system of concentrated charges placed in the pit increases along the borehole axis makes it possible to:

– favour changes in a well network within the bench and intensify the rock mass output from a 1 m well by 5-20% with no decrease in crushing quality in terms of constant specific explosives consumption through the increase in the pit diameter up to 0.36-0.45 m;

– reduce specific explosive consumption by 10-15% under the forecasted yield of the broken rock mass from a 1 m well;

– decrease a drilling amount by 30-35% as compared with a continuous string of explosive borehole.

The research analysis has confirmed the idea that the use of explosive charges with a variable cross-section helps increase the explosion efficiency as well as efficiency and grade of rock mass fragmentation, and provide explosive savings [11], [12]. At the same time, increase in the yield of less than 400 mm fraction (up to 85-90%) has been mentioned [13].

However, since, for example, cavities are shaped in a well thermally depending upon the rock type (quartz should be exclusively available in the rock), a new method of borehole charge formation in polyethylene sleeves of a variable diameter has been proposed [14]. The method was first tested at Poltava Ore Mining and Processing Enterprise.

Industrially, the new design of borehole charge using polyethylene sleeve of a variable diameter was tested during rock mining in the open pits of Dokuchaevsk Flux-Dolomite Integrated Works [15]-[17]. The simplest water unstable explosive of PVS-1U type has been used. The industrial tests have shown a decrease in the prime cost of blasting operations owing to almost 15% reduction in explosive cost, dust and gas emission reduction, and losses of minerals.

As paper [17] shows, fragmentation of the fissured and laminated rocks can be controlled while using charges having the narrowed sections along the borehole axis. A distance between them is equal to 4-6 borehole diameters. Air cavities remain between the charge and the well wall where the narrowed sections are available. Similar results have been obtained when using charges of variable diameters [5]. They help control concentration of explosive energy along its length owing to the formation of a variable cross-sectional axial cavity in the charge. The cavity increases to the wellhead.

Authors of papers [6], [18], [19] point out that the changes in an explosive charge diameter along the borehole height can result from placing hollow inserts of different shapes inside the charge cavity. Volumetric hollow figures proposed by paper [18] consist of a concentrator and a distributor. To increase explosion efficiency owing to energy concentration in the charge and its redistribution, walls of lateral surface of afterbody of the volumetric hollow figures are concaved inside; moreover, they have variable radius of the surface.

Explosive energy redistribution along the column of a borehole charge with its action intensification in subdrilling is implemented by means of turbo blasting while mounting spiral turbolators along the charge axis in its central part [20]. Its function is to produce a torque with the help of $F(t)$ force when detonation wave (DW) is passing through the charge column and impacting it by its head as well as detonation products (DPs) during Δt time. As a consequence, when DW is passing under the influence of gaseous DPs, a progressive rotation pulse is applied to the turbolator in the direction following the DW. The turbolator rotation originates “vortices” providing the forced DP convection, and contributing to more complete explosive combustion in the borehole [21].

Qualitative development of a bench bottom as well as reducing the chances of its heaving, the reinforced explosive charge in the lower part of borehole involves placing a powerful explosive in it or the lower part of borehole expanding and making the hole of 400 mm in diameter. Other methods are also applicable. As the authors of paper [22] mention, it is possible to avoid overdrilling if only explosive charges with air cushion, air cavities, and gaps, placed in the bottom part of the well, are used for rock breakage. It has been defined that achieving a borehole end, the explosive wave (EW) runs back; hence, within its front at the head pressure increases sharply. It has an additional effect on lower part of the borehole favouring the improved development of the bench and decreasing overdrilling length down to 50%.

Some authors note [23] that the nature of complex rock failure depends upon microstructures (i.e. orientation of microcracks and physicomechanical properties of rock-forming minerals) and macrostructures (i.e. spatial position and morphology of cracks crossing the rock mass). Therefore, the achievement of high-quality explosive preparation of rock mass, reduction of mineral losses, and improvement of blasting effectiveness is possible through the selection and substantiation of rational drilling and blasting parameters [24] and the conditions of transferring the explosive substance energy to the rock mass being broken down [25], [26].

It has been determined that applying the technology of block structure rock response with the use of the elongated charges in explosive boreholes with 250 mm diameter and placement of the main charge column in anisotropic rock mass leads to separation of blocks which dimensions are close to maximum allowable for the receiving bin of a crusher (1.2-1.3 m) [27], [28]. The problem can be solved while forming a multigradient rock loading from the explosion charges in the additional shortened intermediate boreholes to reduce the yield of oversized blocks [29].

Control of fragmentation quality while obtaining the forecasted grain-size composition of the blasted rock mass and crushing cost cutting should involve adequation of well network arrangement within a bench and decrease well diameter with rather high productivity of rock mass breakage as well as with its excavation. For instance, under the conditions of copper field in Roşia Poieni open pit (Romania) it was proposed to use 200 down to 150 mm well diameters. The wells were drilled with the help of drilling facilities by Atlas Copco Company with minimum expenditures connected with purchase of drilling assembly and bits of corresponding diameters [30].

The results of industrial tests have shown the advantages of boreholes with a diameter not exceeding 200 mm. Oversize yield did not surpass 1000 mm. Owing to the fact, time was saved to crush outsize blocks; energy consumption was saved; and effectiveness of dump to load/unload rock mass was improved as well as efficiency of a crusher. Efficient use of explosives in a borehole is ensured by increasing length of explosive column and its weight reducing in each borehole down to almost 100 kg. The abovementioned has helped mitigate the impact by a seismic wave on the rock mass being broken down during detonation of explosives, decrease an area of the rock mass breakage, and provide stability of benches (a berm, slope angle of a bench) as well as safety during the ore mass transportation.

Solution of the abovementioned problems needs implementation of urgent measures to improve available and develop new engineering solutions concerning the efficiency of complex hard rock breakage taking into consideration both mining and hydrogeological conditions of mining.

Therefore, the studies, connected with the selection and substantiation of a new design of elongated borehole charges, e.g. differing in their cross-sectional shapes (compared with cylindrical continuous structure charges), are still topical. The studies are the basis to develop rational technological parameters of new resource-saving methods of ground breaking based on the consideration of a fissured-tectonic rock mass structure and anisotropy of their physicomechanical properties.

2. Methods

The Mohr-Coulomb strength condition, considering potential failure as a result of both shear and separation, was applied at the initial stage of the research to describe mathematically rock transition to the disturbed state. According to the proposed strength theory, a mathematical model of blast effect (i.e. shock and detonation waves) of the concentrated bore charges [31], [32] on rock mass in a stope of a development mine working has been developed taking into conside-ration empirical dependences by V.A. Borovikov and I.F. Vanyagin [33]. They were used to calculate radial and tangential components from the blast wave action (i.e. detonation and shock) on the rock mass. However, the empirical dependences are valid only for explosion of concentrated charges; changes in the stress field during explosion of charges having other shapes have not been studied. Therefore, simulation of explosive impact on the environment by means of charges differing from traditional (i.e. cylindrical) shape is innovative; it is performed using a newly developed calculation algorithm.

The practical and experimental data [34], [35] have made it possible to understand that failure of rocks by explosion is characterized by one of fracture types being rock separation from rock mass under the action of tensile stresses.

In this context, energy of explosive transformation is the energy of stress waves and the pressure of gaseous detonation products (GDPs). The energy of stress wave is as follows. During its propagation, it disturbs the rock mass partially through a system of natural microcracks achieving up to 75% of total failure. In the context of following expansion of detonation products, its pressure widens the formed cracks up to the complete rock breaking. Hence, blast action simulation should also involve changes in a stress state of rock mass as well as participation of gaseous detonation products in fracturing.

The stress-strain state of rock mass, permeability of environment, and unsteady movement of gaseous detonation products of explosives in the disturbed rock mass are described using the system of Equations 1:

$$\sigma_{ij,j} + X_i(t) + Y_i(t) + T_i(t) + P(t) = \rho_r \left(\frac{\partial^2 u_i}{\partial t^2} \right),\ i, j = x, y;$$

$$\mu \frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(k \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y}\left(k \frac{\partial p}{\partial y} \right) + q(t) = 0; \quad (1)$$

$$k = f\left(\sigma_{ij}, t\right),$$

where:

$\sigma_{ij,j}$ – derivatives of stress tensor components on x, y;

t – time;

$X_i(t)$ – projection of external forces acting per unit volume of a solid body;

$Y_i(t)$ – projection of forces from the explosion action;

$T_i(t)$ is projection of the forces caused by internal friction acting per unit volume of body; $T_i(t) = -c_g\, \partial u_i / \partial t$;

c_g – damping factor;

u_i – displacement;

$P(t)$ – projection of forces caused by fluid pressure in fracture-pore space;

ρ_r – rock density;

μ – viscosity of GDPs;

p – pressure of GDPs;

$q(t)$ – release rate of GDPs;

k – coefficient of permeability.

As paper [36] has explained, jump of pressure, density and velocity of medium during explosion, i.e. instantaneous jump of parameters has been called a shock wave. However, the word “wave” cannot describe accurately the nature of the phenomenon since usually a wave is characterized by periodicity and frequency; and jump is a single abrupt change. Therefore, the author believes that it is more correct to call the phenomenon as a shock pulse.

In the context of the research, we simulated the explosion action while applying an appropriate load in the nodes belonging to the outline of a cylindrical charge as well as in the angles of triangular- and square-prism charges. The calculations are performed using the finite element method.

In the matrix form, the first differential equation from System 1 is as follows [37]:

$$\left[M_g\right] \frac{\partial^2}{\partial t^2}\{U\} + \left[C_g\right] \frac{\partial}{\partial t}\{U\} + \left[K_g\right]\{U\} + \left\{F_g\right\} = 0\,, \quad (2)$$

where:

$[M_g]$ – mass matrix;

$[K_g]$ – stiffness matrix;

$\{U\}$ – vector of nodal displacements;

$[C_g]$ – damping matrix;

$\{F_g\}$ – force vector within the nodes.

Following parameters are specified for the problem as the initial conditions:

$$\sigma_{yy}\big|_{t=0} = \gamma H;$$

$$\sigma_{xx}\big|_{t=0} = \lambda \gamma H,$$

where:

γ – average weight of the overlying rocks, N/m^3;

λ – horizontal stress coefficient;

H – mining depth.

Boundary conditions are as follows:

$$u_x\big|_{\Omega_1} = 0;$$

$$u_y\big|_{\Omega_2} = 0;$$

where:

Ω_1 – vertical boundaries of the external outline;

Ω_2 – horizontal boundaries of the external outline.

$[K_g]$, $[C_g]$ and $[M_g]$ matrices are obtained through the area of a finite element S [37] integration:

$$\left[K_g\right] = \int_S \left[B_g\right]^T \left[D_g\right]\left[B_g\right] dS\,;$$

$$\left[C_g\right] = \int_S c_g \left[N\right]^T \left[N\right] dS\,;$$

$$\left[M_g\right] = \int_S \rho_s \left[N\right]^T \left[N\right] dS\,,$$

where:

$[B_g]$ – deformation matrix of a finite element and its no-dal displacements conditioned by Cauchy correlations;

$[D_g]$ – matrix of elastic characteristics of the material;

$[N]$ – matrix of form functions of the applied finite element.

The total force $\{F_g\}$, applied in nodes of the considered domain, is equal to the total of forces due to the action of hydrostatic pressure, $\{F_o\}$ explosive momentum $\{F_b\}$ (if necessary), and gas pressure $\{F_p\}$, which is determined by solving a nonstationary problem of GDP filtration in a fractured porous deformable medium, which permeability varies in time:

$$\left\{F_g\right\} = \left\{F_0\right\} + \left\{F_b\right\} + \left\{F_p\right\}.$$

The resulting system of matrix Equations 2 is solved using an iterative conjugate gradient method [38], [39], in terms of which the inconsistencies, arising from the substitution of trial solutions in the original algebraic equations, are coordinated.

Stresses are determined using the defined displacements [37]:

$$\{\sigma\} = \left[D_g\right]\left[B\right]\{u\} + \{\sigma_0\}.$$

In order to obtain a solution at a certain time interval [40], a finite-difference method is used.

To simulate explosion action, we need to set pressure of gases p_0, formed as a result of chemical transformations, in the explosion area. Pressure on the borehole wall is $p_0 = p_d / 2$, where p_d is the detonation pressure, determining the value of impulse and high-explosive action. A detonation pressure is one of the main parameters of shock waves [41], [42]. The detonation pressure values were measured by the authors [34], [35] for three types of industrial explosives. Basing on the data, we can conclude that:

$p_d = 1500 \div 2400$ MPa:

$$p\big|_{t=t_{expl},\, x=x_{expl},\, y=y_{expl}} = \frac{p_d}{2}\,;$$

where:

t_{expl} – blast moment, s;

x_{expl}, y_{expl} – explosion center coordinates, m.

Boundary conditions are as follows:

$$p\big|_{\Omega_1(t)} = p_0;$$

$$p\big|_{\Omega_2} = p_v;\quad p_v = 0.1 \text{ MPa},$$

where:

$\Omega_1(t)$ – time-varying boundary of the filtration area;

Ω_2 – internal outline.

By minimizing the functional related to the second equation in System 1, it can be transformed to the following system of differential equations [43], which solution involved a finite-difference method within a certain time interval:

$$\left[C_f\right]\frac{\partial\{P\}}{\partial t} + \left[K_f\right]\{P\} + \left\{F_f\right\} = 0\,, \tag{3}$$

where:

matrices $[C_f]$, $[K_f]$ and vector $\{F_f\}$ are equal:

$$\left[C_f\right] = \int_S \frac{\mu}{\rho}\left[N\right]^T\left[N\right] dS\,;$$

$$\left[K_f\right] = \int_S \left[B_f\right]^T\left[D_f\right]\left[B_f\right] dS\,;$$

$$\left[F_f\right] = \int_S q\left[N\right]^T dS\,.$$

A calculation scheme of rock mass with a free surface and a square-shaped cross-sectional explosive charge is shown in Figure 1. Fragments of the finite-element grid for explosive charges of different shapes are shown in Figure 2.

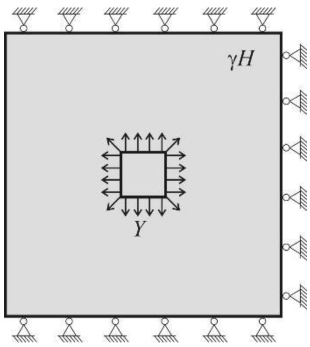

Figure 1. Calculation scheme

(a) (b) (c)

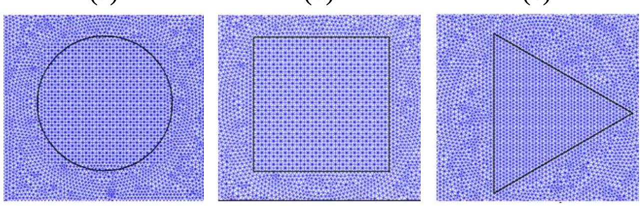

Figure 2. Fragments of a finite-element grid for explosive charges of different cross-sectional shapes: (a) cylindrical; (b) square prism; (c) triangular prism

The initial and boundary conditions for this problem are as follows:

$$\sigma_{yy}\big|_{t=0} = \gamma h; \qquad p\big|_{\Omega_1(t)} = p_0;$$

$$\sigma_{xx}\big|_{t=0} = \lambda\gamma h; \qquad p\big|_{\Omega_2} = 0.1\text{MPa}$$

$$p\big|_{t=0} = p_0; \qquad u_x\big|_{\Omega_3} = 0;$$

$$p\big|_{t=t_{expl},\, x=x_{expl},\, y=y_{expl}} = \frac{p_d}{2}; \qquad u_y\big|_{\Omega_4} = 0,$$

where:

γ – averaged density of the overlying rocks;

h – development depth;

λ – lateral spreading coefficient;

p_0 – initial gas pressure in the fracture-pore space;

t_{expl} – blast moment;

x_{expl}, y_{expl} – coordinates of charge nodes;

p_d – detonation pressure;

$\Omega_1(t)$ – time-varying boundary of the filtration area;

Ω_2 – free surface;

Ω_3 – right vertical boundary of the external outline;

Ω_4 – horizontal boundaries of the external outline.

According to the data from [34], [35], we can say that detonation pressure for main explosives used in practice varies within the range of p_d = 1500÷2400 MPa.

In order to obtain solution of System 1 with the initial and boundary Conditions 2 at a certain time interval, we applied a finite-difference method. In this case, it is assumed that at the initial moment of time $t = 0$, the distribution of stresses and pressures is given, and for sufficiently small values Δt, we obtain the distribution of stresses, gas pressures, flow velocities, and flow rates at time $t + \Delta t$ using iterative relations. This process continues from the initial state to any current moment of time.

To assess the explosive mechanisms of solid fracture by explosive charges of various designs with a variable cross-sectional shape as well as to study the process of occurrence and propagation of stress waves along with the nature of cracking and obtain a qualitative pattern of the medium-breaking process, experimental studies were conducted on the models of optically active materials – organic glass (polymethylmethacrylate) with stable strength, mechanical, and optical constants. A sheet organic glass of constant thickness of 0.015 and 0.035 m was used to make the models. Using a band saw or a circular saw, models of 0.2×0.2 and 0.15×0.2 m were cut out in the laboratory.

The methodology meant three series of experimental studies with different forms of charge cavities: cylindrical, square, and triangular. One part of the experiments was carried out on the models of 0.2×0.2 m and 0.015 m thickness; another part was performed on the models of 0.15×0.2 m and 0.035 m thickness.

Axial lines were drawn on the prepared models with a felt-tip pen for convenient study and evaluation of the crack development nature as well as shape and size of the overgrinding zone. At the points where they intersected, i.e. in the centre of the model (size of 0.2×0.2 m and thickness of 0.015 m), a cylindrical explosive cavity was formed with a drill of 4.5-5.0 mm in diameter throughout the model thickness. Then, using a jigsaw or file, the cylindrical cavity was given a square and triangular shape with an edge of 4-5 mm. Another series of experiments was carried out on the models of 0.15×0.2 m in size and 0.035 m thick in the center of the end part of a narrow edge, which formed cavities with 5-6 mm in diameter and 110 mm in length. A high-velocity explosive (PETN) was placed in the prepared explosive cavities; the explosive mass was 150 mg with the initiator.

The elongated charges of the appropriate cross-section with a constant mass of explosives were formed in the prepared paper profiles. Then, the prepared charges with an initiator were installed in a cylindrical cavity in the model, which mouth was sealed with a plug. The charge was initiated by a nichrome electrode with a high-power electric discharge. When carrying out experimental explosions on the organic glass models, consistency of the cross-sectional area of the charge, its mass, location of the initiation point, and type of explosive used was observed. The model size was selected based on the view size of SFR-2M camera. The main requirements for a medium model are as follows: possibility to record and study the process of cracking and shifting in time; no breakaway phenomena along the model outline during the explosive charge explosion. Views of the charge structures are shown in Figure 3.

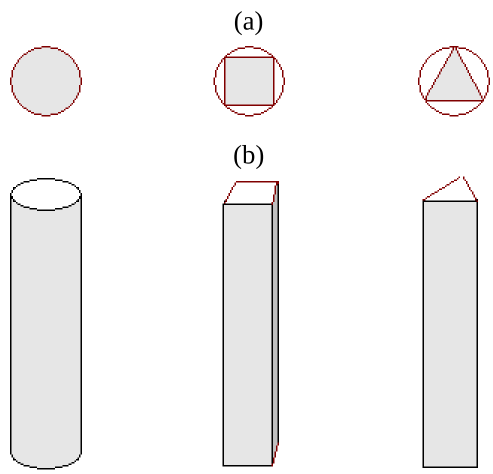

Figure 3. Explosive charge designs with different cross-sectional shapes: (a) cross-section of a charge; (b) view of a charge column

Experimental studies were carried out under the laboratory conditions on a special stand using high-speed photorecording of the process in combination with a polarization-optical method of stress research in terms of time magnifier. The nature of model blasting was recorded with a photorecording device SFR-2M as a part of a special stand having following equipment placed on a horizontal surface: a pulse lamp ISSh-300, a system of lenses focusing a light flux, a control panel, an explosion chamber, batteries of storage capacitors, and an electronic device to synchronize an explosive charge in the model with pulse lamp flashes.

The nature of models' blasting was recorded on KODAK photographic film with a sensitivity of 400-800 units.

According to the experimental research methodology, the recording parameters were set, which were calculated by formulas according to [44]. Calculations according to the represented formulas and test blasting results showed that optimum parameters of filming speed to analyze fracture process and nature of fracture solid, time of borehole start from the explosive charge were ν = 15000 fps and ν = 25000 fps, respectively.

Detonation and synchronization of the process of explosive charge blasting registration in the medium was carried out by including a special electronic device into the stand to synchronize the chamber and pulse lamp operation before it starts working with delayed time of the initiator detonation. Structural diagram of the system is shown in Figure 4.

Consider the principle of block diagram operation. After turning on the control panel of a camera *1*, high-voltage power supply *2* starts up; the capacitor bank *6* is charged from the high-voltage power supply *2* to the voltage of 3 kV.

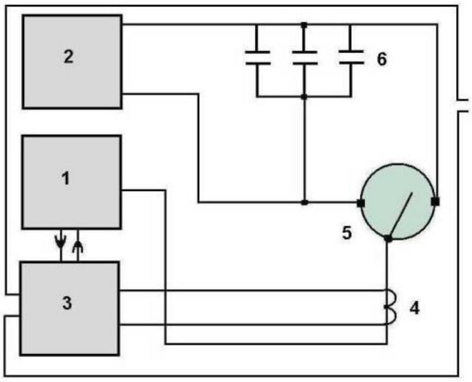

Figure 4. Block diagram of detonation and synchronization of the process of blasting solids by an explosive charge with its high-speed photorecording: 1 – control panel of the chamber SFR-2M; 2 – high voltage source; 3 – device for synchronization and detonation delay of electric detonators; 4 – coil for starting the synchronization device; 5 – pulse lamp ISSh-300; 6 – capacitor bank; 7 – initiator

While transmitting the ignition impulse from a generator from the control panel *1* of SFR-2M camera, the capacitors *6* are discharged onto a pulse gas-filled lamp ISSh-300 *5* with further start of synchronization and delay device *3* by coil *4*, in which EMF is induced from the impulse flowing through its circuit to a pulse lamp. In some delay time, set on the panel of device *3*, explosive charge is detonated in the model by an initiator *7*.

3. Results and discussion

According to the results of simulation modelling of stress field distribution in the mass from the explosion of changes with different cross-sectional shapes and performed calculations, distribution of a geomechanical parameter (parameter *Q*) at various moments of time (time iterations) has been determined, and dependences of changes in the maximal component of the main stress tensor $\sigma_1 / \gamma H$ along the axis passing through the charge centre perpendicularly to its flat surface for various time iterations, represented on Figure 5 and 6, have been developed.

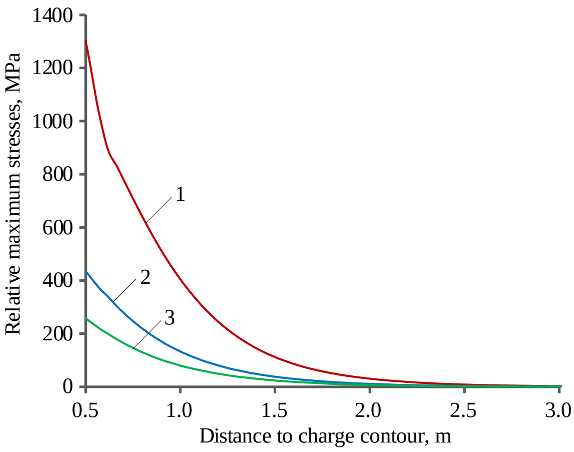

Figure 5. Variation of the maximum component of the principal stress tensor $\sigma_1 / \gamma H$ along the axis passing through the charge centre of a different-shaped cross-section perpendicularly to its surface plane at time iteration equal to i = 3; 1 – cylindrical charge; 2 – triangular charge; 3 – square charge

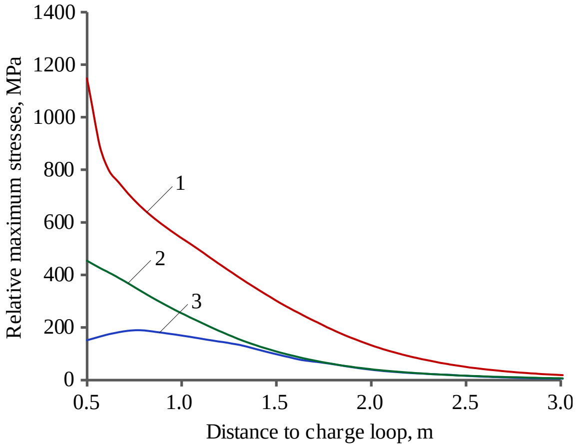

Figure 6. Variation of the maximum component of the principal stress tensor $\sigma_1 / \gamma H$ along the axis passing through the charge centre of a different-shaped cross-section perpendicularly to its surface plane at time iteration equal to i = 5; 1 – cylindrical charge; 2 – triangular charge; 3 – square charge

The calculations have shown that after the DW and EW fronts have passed to the charge outline boundary, the zones of propagation of inelastic deformations around the charges repeat practically the charge outline with smoothed angles; in the course of time, the charge contour levels off, acquiring a circular shape. At this stage of explosion development, a multigradient stress field shifted in time and space is being formed. The obtained dependencies of changes in the maximum component of main stress tensor $\sigma_1 / \gamma H$ along the charge axis show that the nature of stress reduction varies in terms of power dependence. Thus, at the first moments of time – time iteration equal to $i = 3$, the distribution nature is of the same form for all charge types with the only difference that the initial peak stresses for the circular-sectional charge are 3-4 times higher than for the triangular and square ones (Fig. 5). Further, at time iteration equal to $i = 5$ (Fig. 6), numerical values of the maximum tension with the increasing distance from the charge outline depend on the cross-sectional shape (e.g. square prism, Figure 6, position *3*) and vary close to the linear dependence.

The next research stage assessing a mechanism of solid medium failure by explosive charges of different cross-sectional shapes involved experiments on the models with registration of rapid processes by a high-speed photo-recording unit SFR-2M.

According to the camera recording results of the models' fracturing by concentrated and continuous elongated explosive charges of different cross-sectional shapes, the records were made shown in Figure 7.

Figure 8 represents the view of models blasted by charges of different shapes.

According to the records (Fig. 7) and photos (Fig. 8) of a flat model blasted by the explosion of a concentrated charge of various shapes for all series of experiments, we can state the following. The first frames of process registration show that within the range of 0-18 μs after charge detonation, a detonation wave front propagating ahead and its configuration are typical both for a cylindrical shape of charge and for the square and triangular ones. Beginning from 23-28 μs, a shock wave, reflecting from the wall of charge cavity and affecting the blasted medium, creates a stress wave.

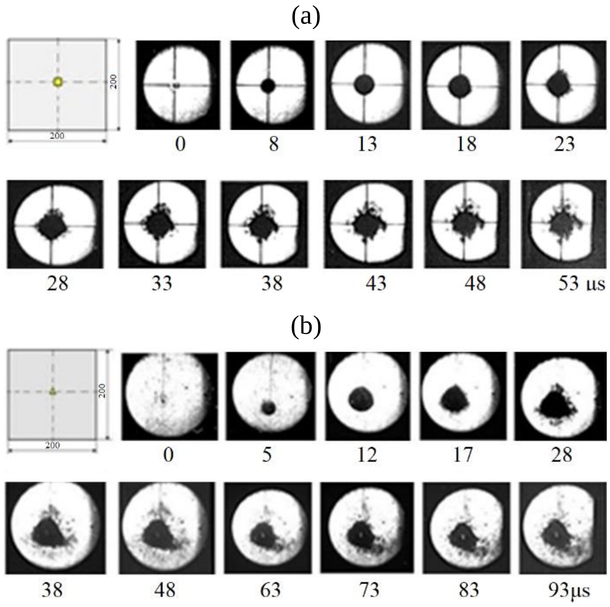

Figure 7. Records of the model blasted by a concentrated explosive charge of different cross-sectional shapes: (a) square; (b) triangular

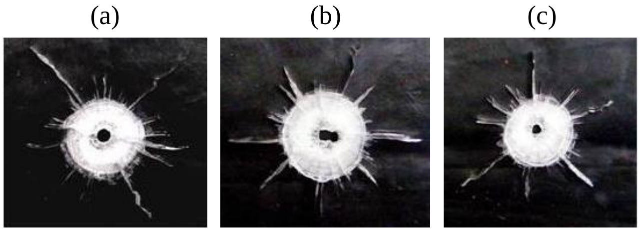

Figure 8. Photo of a flat model blasted by a concentrated explosive charge of different cross-sectional shapes: (a) cylindrical; (b) square; (c) triangular

For a circular charge, it spreads uniformly over the surface along the charge cavity walls, while in triangular and square charges maximum stresses are concentrated in the charge outline corners, contributing the development of a crack system in the model. Within the next time interval of 30-40 μs, stress waves form a crack network perpendicularly to the faces of charge outline in the form of triangular and square prisms.

Analyzing further frames of explosion records of the concentrated charges in the form of triangular and square prisms, one can observe the levelled off stress wave front and nature of crack propagation in the model, being inherent to the circular charges (Fig. 7). In this context, according to the nature of flat model blasting (Fig. 8) by the concentrated triangular and square charges, there is non-uniform distribution of different deformation types around the charging cavity; the nature of these distributions depends on the shape of a charge cross-section. While model blasting, the zones of overgrinding and plastic deformations as well as a dense network of radial cracks of different orientations are clearly visible. We should also note the operation of a charge of circular cross-sectional shape (Fig. 8a). A zone close to the charge is characterized by rather large volumetric deformations, which is reflected in the formation of a significant overgrinding zone. At the same time, a branched network of radial cracks extending to the model boundaries is observed. The main cracks propagate uniformly from the charge in all directions. Therefore, the action of round charges contributes to uniform distribution of stresses. However, when blasting towards the pre-blasted muck pile, uniformly distributed stresses do not provide desired quality of rock crushing and cause formation of cutter breaks in the rear of blasted rock mass. This circumstance complicates blasting conditions during following explosions, which leads to the increased extraction of oversized blocks.

When blasting the model with a triangular prism charge (Fig. 8b), its blasting nature differs somehow from that of a cylindrical charge. Thus, it is possible to specify following characteristic features of such charge operations. The nature of crack pattern is of clear asymmetry. The triangle corners concentrate maximum stresses, favouring the formation of a denser crack network in these zones. The areas with maximum crack lengths have shown that a vector of maximum energy flux density from the explosion of such charge shape is directed perpendicularly to the triangular prism faces, forming a branched network of cracks around the charging cavity with the radius of 5-10 R_c (R_c is charge radius) with following formation of multigradient field of stresses on the charge cavity surface.

It is also necessary to focus on assessing the nature of flat model blasting by a charge having a square cross-sectional shape. Similarly to the triangular-shaped charge, radial cracks formed by the explosion are characterized by clear directionality. Their greatest length with the maximum opening up to the model boundaries is observed at the points of maximum stress concentration – in the corners of a square; the main network of radial cracks perpendicular to the lateral surface of a charging cavity is formed in these nodes. Furthermore, a zone of plastic deformation is insignificant, being equal to 2-3 R_c, while a zone of overgrinding is 3-5 R_c. Analyzing the blasted zone configuration in the model after the square-shaped charge explosion, we can note its coincidence in shape with the zone blasted with a cylindrical charge.

The next research stage was planned to assess the explosion effects of the continuous elongated charges of different cross-sectional shapes on flat models. Analysis of the records (Fig. 9) shows that the blasting front becomes oval at the beginning of the process (8-40 μs) for both triangular and square charges, followed by the formation of clearly marked cracks in the bottom part of a borehole towards the model end-face.

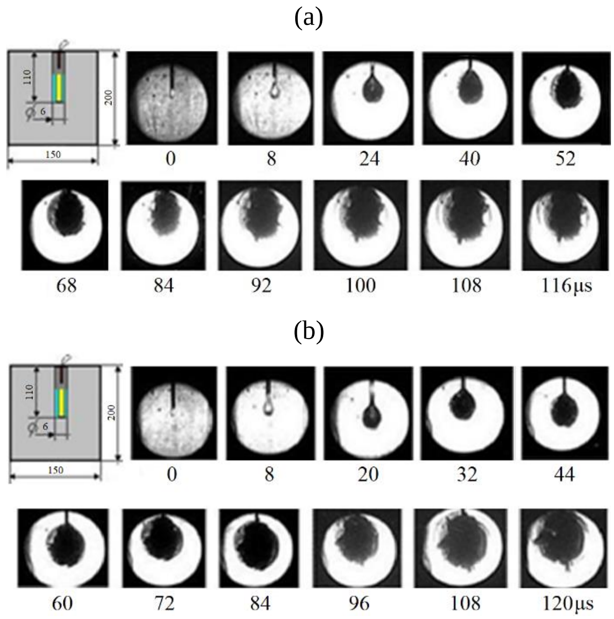

Figure 9. Record of model blasting by elongated explosive charges of different cross-sectional shapes: (a) square; (b) triangular

While further studying of blasting with a square-shaped charge, a slightly different pattern was observed (Fig. 9a). The fracture cavity develops a pear-like shape by the time equal to 50-100 μs and stretches along the charge axis both towards the model end-face and to the explosive cavity mouth. Thus, at the final stage of the process development (100-120 μs), the front of cracking due to square charge explosion moves along the charge axis without essential increase of the fracture zone. A different pattern is observed after the explosion of a triangular-shaped charge; during the explosive cavity development, the cavity tends to a more circular (or rather elliptical) shape with the increasing radius of a blasted zone in radial direction.

Analysis of fracture patterns of the models (Fig. 10) showed that in case of cylindrical shape of a charge (Fig. 10a) radius of the overgrinding zone increases, and zone of plastic deformation decreases without redistribution of explosive energy along its column. A completely different fracture pattern is observed for square and triangular charges. That can be seen in the photos of the blasted models (Fig. 10b, c).

(a) (b) (c)

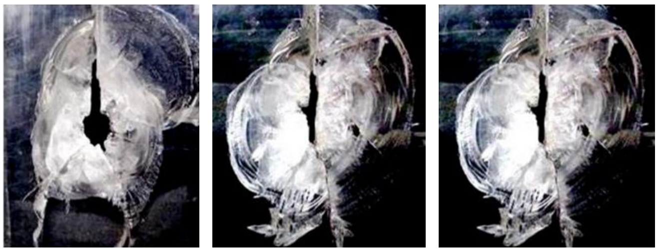

Figure 10. Photo of a flat model blasted by an elongated explosive charge of different cross-sectional shapes: (a) cylindrical; (b) square; (c) triangular

Consequently, in terms of the same mass and increased length of a charge, there is a redistribution of explosive energy in the blasted medium along with the formation of a multigradient stress field shifted in time and space. This leads to a 20-30% decrease in radius of the overgrinding zone and expanded zone of plastic deformation due to growing influence of shear and tensile stresses.

4. Conclusions

Considering the conditions, under which hard rocks are broken, their physicomechanical and structural features as well as the influence of rock mass stress-strain state, the mathematical modelling of rock transition into a disturbed state has been carried out considering the Mohr-Coulomb strength condition. The proposed theory of strength allows considering the possibility of failure as a result of both shear and breakage. According to this theory, a mathematical model of the action of explosion (shock and detonation wave) of the concentrated borehole charges on the rock mass has been developed using the known empirical dependences by V.A. Borovikov and I.F. Vanyagin.

The inelastic deformation zones around the charges at the "explosive-rock" contact have been calculated using the finite element method. According to the results of calculations, distribution of a geomechanical parameter (parameter Q) at different moments of time (time iterations) has been determined; dependences of changes in the maximum stress tensor component $\sigma_1 / \gamma H$ along the axis passing through the charge center perpendicularly to its flat surface at different time iterations have been developed. It is shown that the fall of the maximum component of the principal stress tensor at the initial stage of DW and SW changes according to power dependence.

Analysis of the calculation results has shown that after detonation wave and shock wave front passage to the charge outline boundaries, the zones of propagation of inelastic deformations around the charges repeat practically the charge outlines with smoothed angles; with time, the outline levels off, acquiring a circular shape. At this stage of explosion process development, a multigradient stress field – shear and tensile stresses, shifted in time and space – is formed.

The results of simulation modelling are confirmed by the results of experimental studies concerning qualitative evaluation of a destruction mechanism of solids by explosive charges of different cross-sectional shape on the models of optically active material. It has been defined that the nature of crack propagation in the blasted medium is of clear asymmetry. Thus, maximum stresses are concentrated in the tops of both triangular and square charges; the stresses favour the formation of a much denser crack network in these zones.

It is shown that in terms of the identified sites with maximum crack length, a vector of maximum energy flux density from the charge explosion (both of triangular and square prisms) is directed perpendicularly to their faces, forming a branched network of cracks around the charge cavity within the radius of 5-10 R_c (R_c is charge radius) with subsequent formation of a multigradient stress field on the charge cavity surface. That results in a decrease of the overgrinding zone radius by 20-30% and increasing plastic deformation zone due to growing influence of shear and tensile stresses.

The obtained data of experimental studies correlate with the results of simulation modelling confirming the possibility of influence on fracture dynamics of the complex-structure rock mass obtained from explosive charges of different cross-section shape followed by the formation of a multigradient stress field and initiation of shear and tensile stress peaks on the charge cavity surface.

According to the research results, it is planned to conduct industrial experiments for evaluating breaking efficiency of the complex-structure hard rocks, using the charges of different cross-sectional designs implemented in the corrected blasting patterns while mining building materials in Ukrainian open pits.

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Фізичне та імітаційне моделювання характеру руйнування твердого середовища зарядами вибухової речовини різної форми поперечного перерізу

О. Іщенко, В. Коновал, К. Іщенко

Мета. Експериментальними та теоретичними дослідженнями оцінити механізм руйнування твердого середовища зарядами вибухової речовини різної форми перерізу.

Методика. Для математичного опису процесу переходу гірських порід у порушений стан застосовувались умови міцності Кулона-Мора, згідно з якими розроблена математична модель дії вибуху (ударної та детонаційної хвилі) зосереджених шпурових зарядів. Імітаційне моделювання дії вибуху проведено шляхом застосування відповідного навантаження у вузлах, що належать контуру, як циліндричного заряду, так і в кутах зарядів у вигляді трикутної та квадратної призм. Оцінка механізму руйнування твердого середовища вибухом заряду вибухової речовини різної форми проводилася із використанням методу еквівалентних матеріалів на моделях з оптично активних матеріалів із застосуванням методу швидкісної фотореєстрації процесу у поєднанні з поляризаційно-оптичним методом дослідження напружень.

Результати. На підставі врахування процесу переходу гірських порід у порушений стан застосовано умову міцності Кулона-Мора з можливістю моделювання руйнування як у результаті зсуву, так і в результаті відриву за розробленою математичною моделлю. В результаті розрахунків встановлено розподіл геомеханічного параметра (параметр *Q*) у різні моменти часу (часові ітерації) та побудовано залежності зміни максимальної компоненти тензора головних напружень $\sigma_1 / \gamma H$ вздовж осі, що проходить через центр заряду перпендикулярно його плоскій поверхні для різних часових ітерацій . Встановлено, що у вершинах заряду форми перерізу, як трикутної, так і квадратної призм концентруються максимальні напруження, які сприяють формуванню більш густої мережі тріщин у цих зонах.

Наукова новизна. Встановлено, що максимальні значення компоненти тензору головних напружень $\sigma_1 / \gamma H$ вздовж осі, що проходить через центр заряду перпендикулярно його площині поверхні, на початковому етапі вибуху змінюється за ступеневою залежністю зі зростанням відстані до контуру заряду. При цьому, для форми заряду, наприклад, квадратна призма, при часовій ітерації, рівній $i = 5$ головні напруження спадають за лінійною залежністю.

Практична значимість. Виконані дослідження можуть бути основою розробки раціональних параметрів ресурсозберігаючих способів відбійки міцних гірських порід складної будови в умовах кар'єрів будівельних матеріалів.

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