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Modeling rock destruction under blasting of closely spaced borehole charges

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Abstract. The design scheme is developed, and simulation of radial cracks growth under blasting of closely spaced borehole charges is carried out. The case studies of confined explosion of two charges located in neighboring boreholes are considered. Blasting of decoupled charges in neighboring boreholes is investigated. The free surface effect on a shape and size of radial cracks under explosion of two closely spaced boreholes rising to the surface is simulated. The blast pattern to gain the maximum size of the destruction zone is determined.

1. Introduction
The mining blasting operations are mainly realized by coyote blasting technique. According to the design pattern a number of blast holes are preliminarily made in blasting rocks. The blasthole pattern parameters: spaces between holes in a row and between rows are determined in terms of a size of a rock breaking zone made by blasthole charges. Estimates of a size of such zones are reported in publications [1–3]. It is essential to consider interaction of neighboring charges under concurrent blasting in order to make a precise theoretical evaluation of a breaking zone size.

In blasting of elongated pre-charges and blasthole charges in brittle monolithic rocks the destruction is mainly falls on the zone of radial cracks. The software to compute the evolution of uniformly angularly distributed flat radial cracks is developed with 3D problem statement in order to estimate a size and a shape of such cracks induced by blasting of an alongated preset-length charge [4]. In compliance with the zone model of blasting [5–7], the detonation of a charge in-depth of a rock mass is followed by propagation of an elastic compressive wave and later by the destruction-wave front. In the course of wave propagation the elastic wave stress tends to decay, and the destruction wave front is slowed down. The generation and evolution of radial cracks gets feasible within the interval when a velocity of the destruction wave evolution lowers, fracturing gains the maximum velocity of its propagation, and azimuth tension stresses arise [3, 8]. Thereto the destruction-wave front comes to a stop, the radial shear of the elastic medium is fixed at the boundary with broken rocks. The elastic medium expansion gained in the first stage of blasting used to preserve due to the broken rock resistance to radial compression. The broken rock is prone to deformation under Coulomb friction law. Such expansion leads to development of a radial crack system in an elastic zone of a rock mass. As the final size of radial cracks under blasting appears much greater than radius of a breakage zone, the assumption is made in modeling that the fracturing starts in the elastic plane from an initial radial system N of orthogonal cracks which originate at axis of an extended charge, and their dimensions are equal to a charge length and a radial size of the destruction zone r_d. The initial crack edges are supposed to be under constant pressure p_d, stimulating opening of cracks d_0 in pursuance of displacement of

boundaries of the elastic zone and the destruction zone resulted from the first-stage blasting effect. To establish a shape of radial cracks in the final stage of their dynamic development, the researchers consider the quasi-static process of the crack development under conditions of a continual increase in opening d_0. At every design stage starting from the initial one the stress state of the elastic medium is estimated nearby the front of cracks in view to establish a probable destruction of a medium and development of a crack.

2. Numerical simulation and results analysis

The paraclase technique is employed to calculate 3D stress state of the medium in an elastic space with a radial system of uniformly angularly distributed flat cracks being under internal pressure [8, 9]. According to this method the crack surface is divided into square elements at pitch a, within these elements the opening and shear of crack edges are assumed constant. Thus, a crack is represented by a set of dislocation elements, described by Burgers vector, which components can be unknown in advance. They are computed in terms of the requirements to fulfill boundary conditions concerning stress in centers of dislocation elements by solving a respective system of linear equations. Coefficients of these systems are coefficients of mutual influence of elements on each other. The influence coefficients were calculated by Pitch–Keller formulas where stress tensor components are presented in a random point in an elastic space in the vicinity of a dislocation discontinuity through contour integrals along its boundary. The same formulas were used to calculate stresses nearby crack edges in order to identify their evolution.

To simplify the study problem on the influence of charge interaction in blasting, the study case of development of a radial crack system, consisting of two flat cracks in a plane of axes of neighboring blastholes was considered.

Estimating calculations of destruction parameters under blasting of closely spaced blasthole charges were performed for a few configurations shown in Figure 1. Scheme in Figure 1a demonstrates two blasthole charges loaded in neighboring blastholes.

As an example of calculations by this scheme, in Figure 2a the first quadrant of plane (x, z) in dimensionless form, referred to a calculation grid space $a = 0.5$, contains the shapes of radial cracks induced by blasting of two charges of 40 in length, loaded in neighboring blastholes with space $2h = 12$ between them, the initial crack openings being different. It is obvious that increase in opening leads to fusing of cracks into one, the front of the resultant crack embraces both charges. Efficiency of blasting of two neighboring blasthole charges can be evaluated by fracturing area S. The relationships of this area versus spacing between blastholes are presented in Figure 2b for different values of initial crack openings d_0. It is evident that there is distance $2h$, at which the crack has the maximum area.
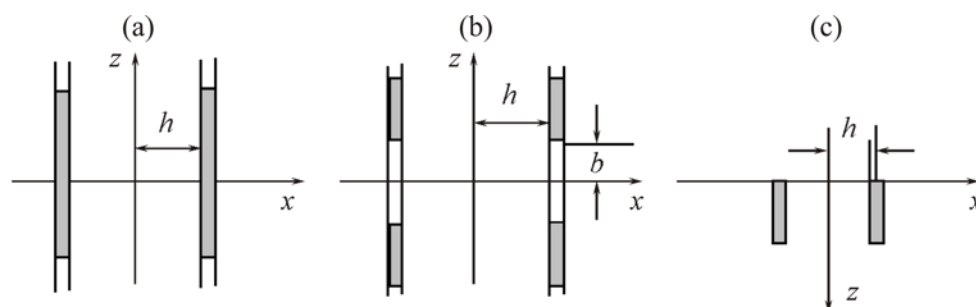

Figure 1. Pattern of blasthole charges: (a) two charges in neighboring lastholes, (b) four charges in two neighboring blastholes, (c) two rising-to-the-surface charges in two neighboring blastholes.

It follows from diagrams in Figure 2b that distance between blastholes, at which the area of cracks is maximum, depends on the initial crack opening, governed by the specific explosive consumption.

According to the calculation data the optimal space is proportional to a transverse asymptotic value of crack size b_m, generated by blasting of a single long charge: $h \approx 1.1 b_m$.
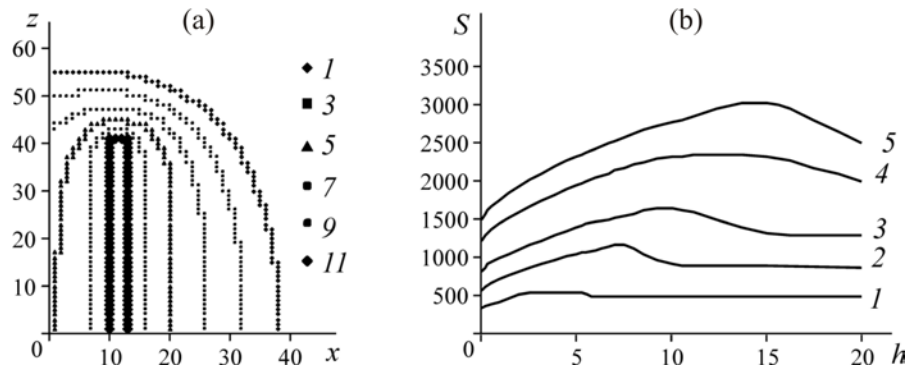

Figure 2. Destruction effect of two long charges in neighboring blastholes (Figure 1a): (a) shape of fractures at their differing initial opening in the first quardrant (curves *1–11* correspond to values: $d_0 = 0$, 0.2–1); (b) dependences of crack area S vs. distance $2h$ between blastholes at the initial openings: $d_0 = 0.3, 0.5, 0.7, 1, 1.2$ (curves *1–5*).

It can be stated from blasting experience that quality of blasting is higher at the uniform distribution of the charge along blasthole length. The charge is divided into fragments and distributed uniformly in a blasthole with gaps $2b$ relative to each other. Figure 1b illustrates such disposition of four charges. The calculation of crack evolution under simultaneous blasting of four charges loaded at such charge pattern is shown in Figure 3 as an example. Figures 3a and 3b demonstrate in the first quadrant the dimensionless form of cracks shapes induced under blasting of four charges of length 20, loaded by pairs in blastholes with gaps $2b = 4$; 8 at space between holes $2h = 8$; 16, respectively. Curves *1–8* are for crack shapes, corresponding to blasting of different-diameter charges; in calculations different diameters are characterized by different values of initial crack openings d_0.
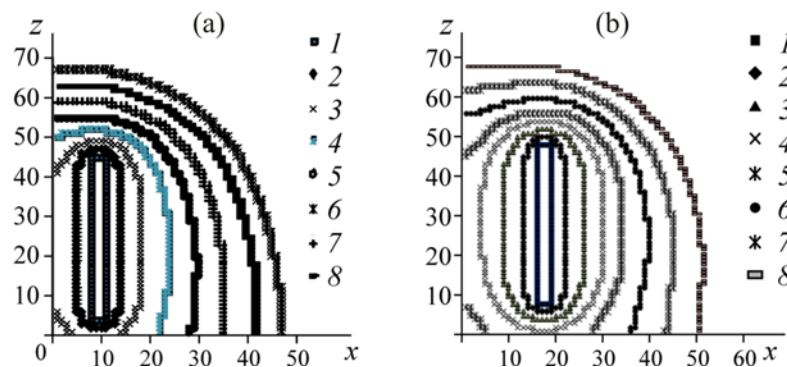

Figure 3. Destruction effect of four elongated charges in neighboring blastholes (Figure 1b): (a) crack shapes (in the first quadrant) at differing initial crack openings at $b = 2$, $h = 4$; (b) crack shapes (in the first quadrant) at differing initial crack openings at $b = 4$, $h = 8$. Curves *1–8* correspond to values: $d_0 = 0$, 0.2–1.4.

Analysis of calculation results at different values of parameters $b = 1$–6 and $h = 2$–12 revealed that there are intervals of charge dislocations relative to each other, at which the common crack area embracing these four charges is maximal. Approximately such charge disposition is determined by ratios: $h \approx b_m$, $b \approx b_m /2$. Figure 4 demonstrates diagram of dependence of the crack area around four charges on intervals h and b for a charge, which initial opening amounts to $d_0 = 0.9$. Column rows 1, 2, 4

are for blasting of charges with parameters $b = 1, 2, 4$. The maximum value $S = 2033$ is gained at inter-charge gap $2b = 6$ in a blasthole and inter-blasthole space $2h = 9$.
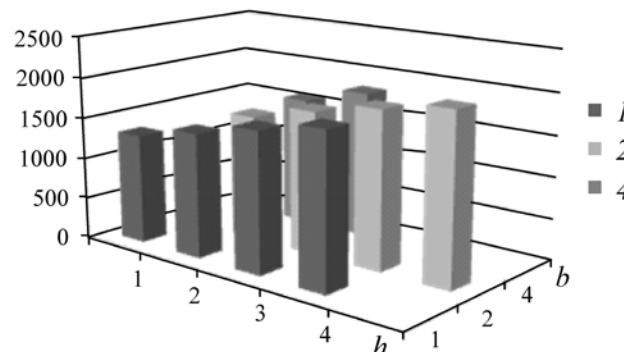

Figure 4. Diagram of dependence of dimensionless area of a crack, generated under blasting of four charges, versus charge dislocation distance h and b.

In the case when an elongated charge starts from the surface the shape and size of the radial crack zone should be evaluated with account for the free surface effect. The software is developed to solve problems where free surface is modeled as a load-free flat crack of a large size as compared to charge length [4].

The calculation is made for the problem of crack evolution under simultaneous blasting of two downhole charges loaded in neighboring blastholes spaced at distance $2h$ from each other (Figure 1c).

As an example Figure 5a demonstrates in the first quadrant the planes (x, z) of radial crack shape induced under blasting of two charges of length $l = 14$ with interval $2h = 12$ between blastholes with different values of the initial crack opening $d_0 = 0, 0.2 - 1.4$ (curves $1–8$). From calculations of crack sizes and their areas it can be set forth that there is distance between blastholes, at which the fracturing area is maximal. It is explicit in Figure 5b where relationships of the fracturing area in its dimensionless form versus distance h at different openings of initial cracks d_0 are shown.
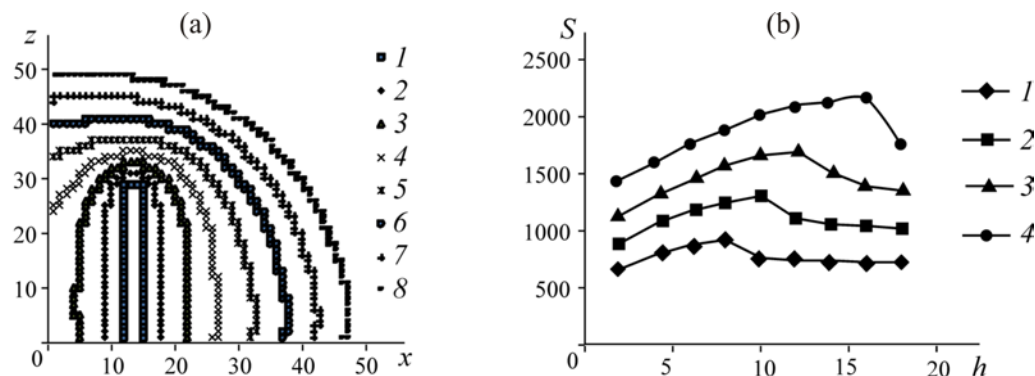

Figure 5. Calculated results on crack evolution under simultaneous blasting of two cord charges rising to the surface: (a) calculated crack shapes in the first quadrant at different values of initial crack openings; (b) relationships of crack area vs. intercharge distance h at some initial crack opening values $d_0 = 0.6, 0.8, 1.0, 1.2$ (curves $1–4$).

Comparison of the optimal distance between neighboring blastholes with the size of cracks in axial and lateral directions revealed that the inter-hole space providing the maximum fracturing area is close to a value of growth of a crack initiated by a single charge rising to the surface at lateral direction $h \approx b_m$.

3. Conclusions

The calculation scheme of modeling the crack evolution in blasting closely spaced blasthole charges is worked out.

The study cases of confined blasting of two and four charges loaded in neighboring blastholes are considered.

The free surface effect on a shape and size of radial cracks in blasting two downhole charges loaded in neighboring blastholes is investigated. The parameters of charge disposition at which a size of destruction zone can be maximal are established. Such parameters enable to cut down explosive consumption rate in drilling operations with mass blasting, controlled blasting, blasting with slot formation in a rock mass.

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