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Numerical Simulation of the Failure Localization for Rock Massive Under Rock Pressure Conditions During Explosive Mining with Charges of Industrial Explosives

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Abstract

The complication of geomechanical conditions with an increase in the depth of field development requires improved calculations of drilling and blasting parameters based on studies of the patterns of changes in the stress-strain state and fragmentation of the blasted massif with an increase in rock pressure in various directions. This paper presents the results of studies of a section of a rock mass with a bare surface under conditions of flat deformation by the smoothed-particle hydrodynamics (SPH) method when blasting blasthole charges of sparing and crushing action. Regularities of change in time and space of the destruction zones of the massif and stresses with the formation of cracks as a result of the impact of an explosion in the presence of external pressure and in its absence are established. The results of calculations of the influence of physical and mechanical properties on the trigger effect of the destruction of the blasted rock are presented. To obtain preliminary estimates of the growth and branching of crack-like defects in real rocks under plane deformation conditions, numerical experiments were carried out. Diffraction patterns of fracture development on cracks filled with sand are obtained.

Keywords: Explosive; Explosion zones; Geomechanical conditions; Numerical modeling; Smoothed-particle hydrodynamics method (SPH)

1. INTRODUCTION

To date, there is an extensive literature devoted primarily to the study of the static distribution of stresses and fracture zones near cracks and cuts. In this case, the basic solution is the solution of problems for an elastic plane with an elliptical hole, which makes it possible to apply the methods of the theory of functions of a complex variable. Dynamic problems in the theory of cracks and problems of wave diffraction by cracks have been studied to a much lesser extent. This is primarily due to the difficulty of obtaining an effective mathematical solution, since the classical method of separation of variables is not applicable to an elastic body with a crack in the dynamic case.

Dynamic problems for bodies with cracks are divided into two classes: wave diffraction on stationary cracks and crack propagation. Recently, some studies have also appeared that consider the interaction of elastic waves with moving cracks. In this paper, problems of the first class are considered. Typical results are given on crack formation and diffraction of fracture zones on stationary cracks filled with inert material.

The relevance of the research is due to the need to expand the possibilities of controlling the action of an explosion in order to obtain a rational fragmentation of the rock mass due to rapidly changing mining conditions for the development of deposits and the tightening of requirements for industrial safety of mining operations.

The research is aimed at developing the theory of rock mass destruction and geomechanical substantiation of innovative mining technologies in the complex development of subsoil. The research methodology is based on the combined use of computer modeling and experiments on compositional simulation models for calibrating numerical calculations. Simulation compositional models contain color-coded zones of explosion action at three levels by distance from the center of the charge and include inclusions of rock samples and crystalline raw materials [1–5].

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The subject of research is the fundamental regularities that characterize the destruction of rock masses by an explosive method in complex mining and geological conditions at great depths, as well as explosive media in the process of special blasting.

2. DESCRIPTION OF THE SIMULATION

Studies are being carried out on the regularities of the influence of the explosive characteristics of industrial explosives (IE) and external pressure on:

– intensity of crushing and parameters of fracture zones and propagation of radial cracks under various loading conditions of explosive media, including rocks;

– changes in time of the voltage values arising in the explosive medium at different distances from the charge;

– changes in the output of fine fractions;

– changes in the speed and distance of fragments scattering.

An explosion as a trigger effect is often responsible for triggering one or another process that radically changes the geomechanical state of the developed rock mass. Trigger effects in studies of the action of detonating explosive charges consist, in particular, in the destruction or disruption of contacts between individual blocks of rocks, which are considered in conjunction with an increase in the level of stresses in the massif under the influence of the energy of the explosion. Peculiarities of the impact on the rock of the impact of a "sparing" explosion with the use of explosives ANFO and the crushing action of explosive charges of TNT and other energy-intensive materials are considered.

Interpretation of the results of experiments on the explosive destruction of geomedia requires realistic modeling of the behavior of materials. When studying explosive processes with significant displacements and destruction, commensurate in scale with the structural inhomogeneities of the medium, it is necessary to use the mesomechanical approach. This makes it possible to study directly from the results of numerical simulation those physical features of the response of the geo-environment to the impact of an explosion that cannot be obtained, for example, using mixture models that replace a structurally inhomogeneous medium with a homogeneous medium with effective parameters.

As the experience of calculations has shown, the method of smoothed particles is the most suitable for solving problems of mesomechanics, in which the processes of explosive destruction on the scale of the structure of the geomedium are considered [3–11]. The absence of a computational grid makes it possible to naturally calculate arbitrary rotational and shear displacements of the material, the decay of simply connected and the merging of multiply connected computational domains. Moreover, the chosen method gives a physically correct picture of the evolution of the displacement of material fragments in cases where the use of numerical Lagrangian grid methods becomes in principle impossible due to unacceptable distortions of the computational grid.

To study the regularities of controlling the impact of explosive destruction of blast-hole and borehole explosive charges having different designs and explosive characteristics, three types of approaches were tested for numerical modeling of the processes of initiation of dynamic events and interpretation of observational data — these are the solutions of a number of problems of plane deformation with layer symmetry, an axisymmetric problem, and also three-dimensional problem of destruction within the area of the blasted block of rock. The design schemes of axisymmetric and plane problems allow, on the one hand, enough describe in detail the behavior of real simulation models, on the other hand, they greatly simplify the computational analysis of the process.

To solve the problems under consideration, boundary value problems were formulated within the framework of the model of an elastoplastic body of continuum mechanics [12,13], which were solved by the method of smoothed particles, which positively recommended in solving dynamic problems of geomechanics [6–11]. The advantages of the Lagrange, gridless ideology of the smoothed particle method make it possible, when using it, to reveal the features of wave processes and the nature of the destruction and fragmentation of the geo-environment. Peculiarities of the influence of energy saturation of charges on the kinetics of fragmentation of destroyed rocks were revealed [3].

Solution of the axisymmetric problem of the impact of an explosion of charges with air gaps [4] made it possible, in particular, to establish the effect of the gap between TNT explosive charges and the charging cavity on the yield of fractions less than 1 mm, as well as to reveal the nature of the change in the fine fraction yield with a change in the gap between the charge and the wall of the charging chamber and when replacing individual high-energy explosives with mixed compositions containing ammonium nitrate.

An assessment was made of the influence of air gaps and well diameters on the uniformity of rock mass crushing [4,5].

As a result of the research, the functions of changing the fragmentation of individual sections of explosive media depending on the change in tangential and radial stresses at characteristic points in solving problems of the action of borehole charges under plane deformation conditions, on the nature of the change in the first invariant of the stress tensor when using three-dimensional models, as well as on the following influencing factors:

– physical and mechanical properties of rocks;
– distances from charges of industrial explosives (IE) with different kinetics of energy release;
– specific consumption of PVV;
– distances to the free surface and its configuration;
– charge diameter and distance between wells;
– the size of the air gaps between the charge and the wall of the charging cavity;
– density of PVV.

Figure 1 presents in the form of a diagram the results of studies of the effect of a change in the density of explosives on the critical strength of the geo-environment at which the trigger effect of its destruction occurs.

In the present study, under conditions of plane deformation, the method of smoothed particles simulated the process of loading and destruction of a section of rocks with blasthole charges with a diameter of 28 mm and 30 mm of gentle and crushing action under conditions of external pressure up to (25 MPa) and in its absence.

The formation of cracks subperpendicular to the axis of simple tension occurs when the normal tensile stress on the surface perpendicular to the axis of tension becomes higher than the value $\sigma_s \approx E/100$ — the tensile strength of rock cohesion. Rocks are not a homogeneous continuous medium. There are small cracks and inhomogeneities, including defects at the grain boundaries. The criterion of fracture by separation used in the calculations makes it possible to determine the zones of the destroyed material under explosive loading.

Figure 2 shows the patterns of localization of cracks that arose as a result of the explosive action of ANFO and TNT charges on a section of the massif that initially had no cracks. An analysis of the data obtained during the simulation showed that the crack propagation zone is at least 70 cm from the charge and the free surface.

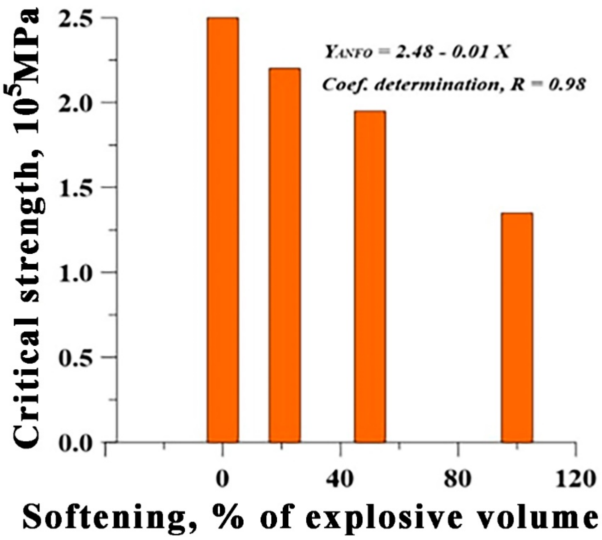

Fig. 1. Influence of deconsolidation of the explosive medium on the critical strength of the explosive medium at which the trigger effect of its destruction occurs.

In this case, the average distance between newly formed cracks in the near zone of action of an explosion with a radius of 25 cm is 4.54 cm and 2.22 cm, respectively, for a charge of sparing and crushing action. The average distance between cracks outside the near zone of the explosion was 20.4 cm and 13.3 cm, respectively. Calculations using the method of smoothed particles showed that the use of TNT instead of ANFO leads to a decrease in the average piece of the exploded mass by 51% and 35%, respectively, in the near and in the area of radial crack formation, respectively, however, this increases the yield of small fractions. The influence of the kinetics of the release of explosion energy and the systematization of explosive media according to the degree of resistance to

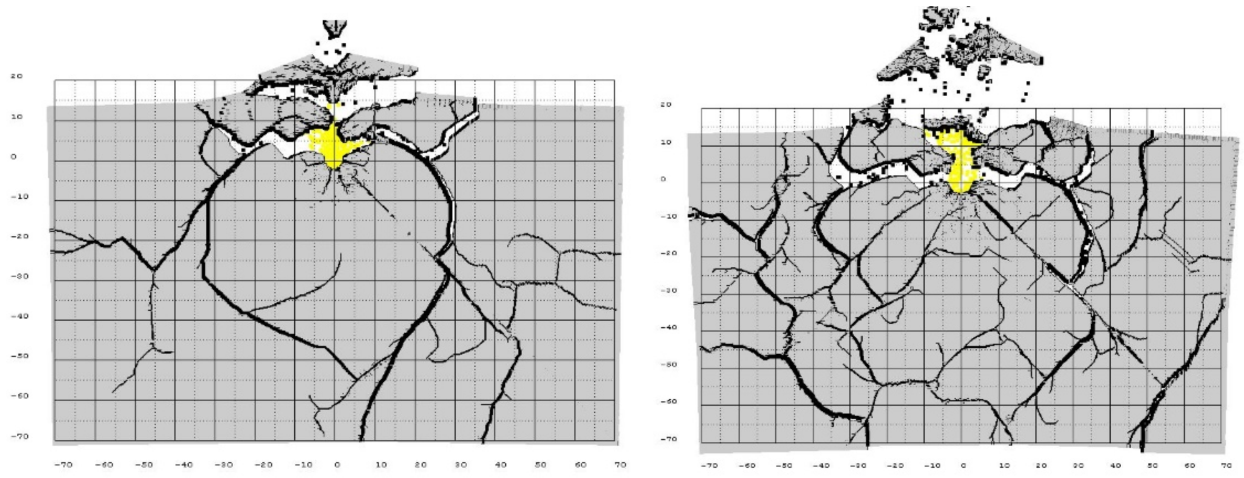

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Fig. 2. Localization of cracks when using a charge of sparing (a) and crushing action (b) TNT without external pressure on a section of the geo-environment destroyed by the explosion, which initially does not have cracks.

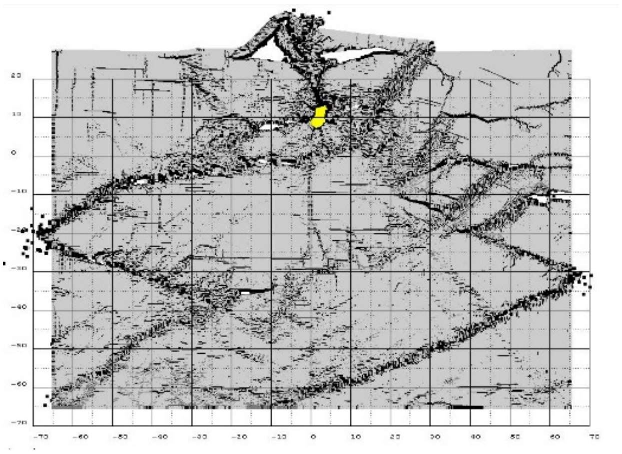

Fig. 3. Localization of cracks with simultaneous impact on the destructible massif of an explosion of a sparing action charge ANFO and pressure in two directions.

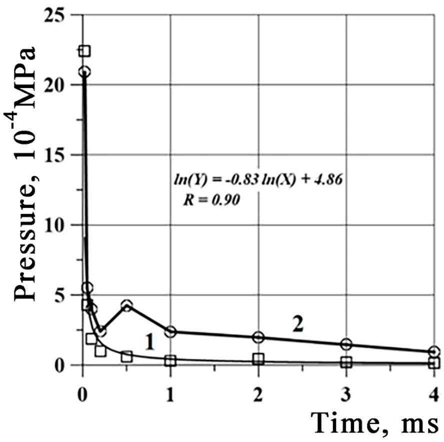

Fig. 4. Dependences of the stress index in an explosive environment using a TNT blasthole charge on the duration of the explosion in the absence of external pressure (1) and its presence (2).

the effects of an explosion are considered in Refs. [1,2]. The peculiarities of the change in time and space of stresses arising in a medium being destroyed under the influence of ANFO and TNT charges are considered by us in Ref. [3]. To calibrate the models, the deformation-strength characteristics of the medium and the energy parameters of the means of destruction of simulation composite models used in full-scale physical experiments conducted in 2021–2022 at the IPPC RAS test site were taken as a basis [5].

Figure 3 shows the results of modeling by the method of smoothed particles of the localization of destruction as a result of the combined action of an explosion of charges with different energy saturation and pressure on the destroyed section of the rock. The compression of the array was carried out with the same intensity in two directions: parallel and perpendicular to the free surface.

An analysis of the localization of fracture zones shows that under the explosive action of ANFO and TNT charges on the compressible section of the massif, the propagation zone of radial cracks was significantly reduced, and the yield of fine fractions in both zones of the explosion increased. As a result of the impact of pressure, linear sections of pre-fracture were formed, oriented mainly at angles of 35–45 degrees to the boundary of the free surface of the section of the array. The average distance between the fracture planes formed by the impact of bilateral pressure and explosive load with a sparing and crushing charge was 15.5 cm and 11.38 cm, respectively.

The time dependences of the voltage indicator that occurs in an explosive environment with the use of a TNT charge in the absence and presence of external pressure are shown in Figure 4.

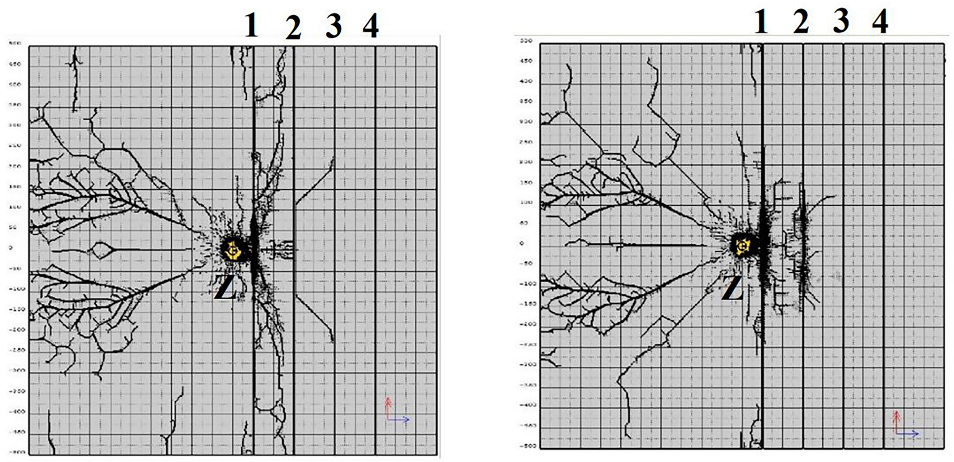

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Fig. 5. Localization of cracks in a monolithic array (to the left of the charging cavity) and an array with stationary cracks 10 mm wide (a) and 20 mm wide (b) as a result of the explosion of a charge with ammonium nitrate EHV in a well with a diameter of 200 mm. Z – camouflage cavity; 1, 2, 3, 4 – stationary cracks filled with sand.

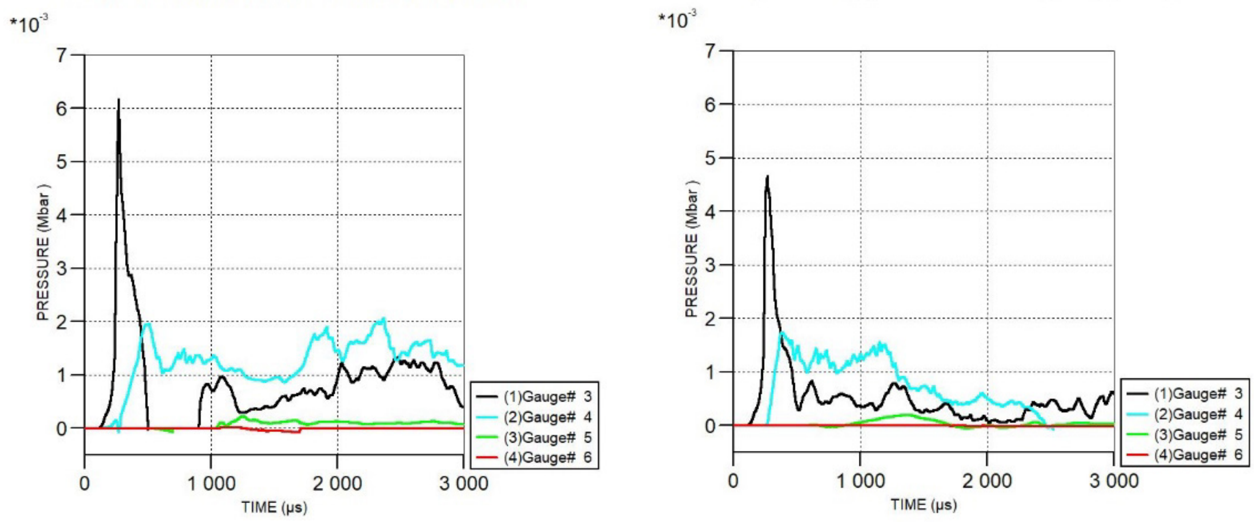

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Fig. 6. Change in the value of the first stress tensor invariant before the first crack (line 1) and after (line 2) and before the second crack (line 3) and after (line 4) for cracks 10 mm (a) and 20 mm (b) wide.

Numerical experiments were carried out by the method of smoothed particles [5] of the influence of cracks of various widths on the formation of zones of localization of destruction of a rock mass under explosive loading. Figure 5 shows a "map" of crack propagation in a 5×5 m block from an explosion of an ammonium nitrate explosive charge with a diameter of 200 mm. An analysis of the results obtained indicates that during the explosion of a mass near a stationary crack 10 mm wide and filled with sand, the radius of the fragmentation zone by a system of longitudinal and transverse cracks decreased from 5.0 m to 2.0 m, while near a crack 20 mm wide, the radius of the fragmentation zone system of longitudinal and transverse cracks decreased from up to 1.5 m.

According to the nature of destruction, rocks can be classified as brittle or quasi-brittle materials. The destruction of rocks under plane deformation conditions depends on the type of loading and rock structure. Branching and fracture of crack trajectories under the combined action of tensile and shear stresses shows that the rock fracture occurs in quasi-brittle and brittle types.

Using the results of the numerical experiments, the curves of the change in the values of the first invariant of the stress tensor at characteristic points directly in front of and behind the location of stationary cracks were plotted (Fig. 6).

Figure 6 shows that an increase in the width of the crack weakens the stress-strain state of the rock. Processing and comparison with theoretical assumptions of the obtained dependences of the fracture angles and the length of fracture trajectories on the parameters of the stress state under explosive loading make it possible to reveal the effect of crack sizes on the nature of fracture and rock fragmentation during blasting.

3. CONCLUSION

1. Numerical experiments were carried out by the method of smoothed particles of the combined impact on the area of the rock mass of pressure and energy of the explosion of charges of sparing and crushing action.

2. The nature of the effect of decompaction of explosives on the critical strength of the geo-environment has been established. The dependence of the critical strength of the geo-environment destroyed by the explosion at which the trigger effect of its destruction occurs on the explosive density is linear within the studied range of values.

3. Features of the localization of radial cracks from the impact of the energy of the explosion of ANFO and TNT charges in the area of an unloaded rock and under constant external pressure are established. When loading the rock mass model in two directions, a system of cracks appears that prevents the propagation of radial cracks located at an angle of 35–40 degrees to the free surface.

4. A comparative assessment of the change in the average distance between cracks and the output of fine fractions was carried out. The output of small fractions under the combined effect of pressure and explosive load on the massif with ANFO and TNT charges increased by 2.8 times compared to similar indicators of the impact of the explosion of blast-hole charges on an unloaded massif. This is due to a significant difference in the values and nature of the change in time of stresses in the geo-environment in the presence and absence of external pressure.

5. Numerical modeling by SPH method for fragmentation of fractured and monolithic sections of a rock mass makes it possible to determine the change in the zone of controlled crushing under the influence of the explosion energy of various explosives. The presence in the array of

a system of stationary cracks 10 mm wide with a distance between them of 1 m leads to a reduction in the crushing radius by a factor of 5, while for similar cracks 20 mm wide, a decrease in the radius by a factor of 7.

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Численное моделирование локализации разрушения горного массива в условиях горного давления при взрывных работах зарядами из промышленных взрывчатых веществ

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Аннотация. Усложнение геомеханических условий с увеличением глубины разработки месторождения требует совершенствования расчетов параметров буровзрывных работ на основе изучения закономерностей изменения напряженно-деформированного состояния и фрагментации взорванного массива при повышении горного давления в различных условиях. В статье представлены результаты исследований участка горного массива с оголенной поверхностью в условиях плоского деформирования методом гидродинамики сглаженных частиц при подрывах зарядов щадящего и дробящего действия. Установлены закономерности изменения во времени и пространстве зон разрушения массива и напряжений с образованием трещин в результате воздействия взрыва при наличии внешнего давления и при его отсутствии. Представлены результаты расчетов влияния физико-механических свойств на триггерный эффект разрушения взорванной породы. Для получения предварительных оценок роста и разветвления трещинообразных дефектов в реальных горных породах в условиях плоского деформирования были проведены численные эксперименты. Получены дифрактограммы развития разрушения по трещинам, заполненным песком.

Ключевые слова: плотность взрывчатого вещества; зоны взрыва; геомеханические условия; численное моделирование; гидродинамический метод сглаженных частиц