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A Study of Gas-Dynamic Processes in a Charge Chamber during the Explosion of Blasthole Charges of Various Designs.

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ABSTRACT

The paper describes a mathematical model for the calculation of the parameters of dynamic loads on the wall of a blasthole (well) during the explosion of charges having various designs and different initiation modes. It presents the results of the calculations of a stress wave in the rock mass from the explosion of a blasting charge, and the gas-dynamic parameters in the charge chamber of a blasthole (well).

Keywords: gas-dynamic task, rock mass, detonation, explosive.

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INTRODUCTION

The work of destruction of rocks by the action of an explosion is performed due to the internal energy of charge detonation products. Therefore, the condition of the explosion products contained in the explosion cavity significantly affects the work performed by an explosion and determines not only the amount of shattered rock, but also the quality of destruction.

The distribution of the amount of energy, transferred to the rock by an explosion, in the near-field of the charge depends on the compressibility of the rock. It is known that the most part of the energy, released during the chemical transformation of an explosive, is absorbed in the near-field of an explosion, which considerably reduces the efficiency of blasting. By determining the coefficient of the transfer of the energy of an explosion to the rocks, it is possible to solve the problem of choosing an explosive for the most effective destruction of the rock mass (Bersen'ev, 1999; Stavrogin and Tarasov, 2001).

The works (Borovikov and Vanyagin, 1976; Mashukov *et al.*, 2007) present the results of an explosion in rocks different in their physical and mechanical properties. There are correlation dependences between these properties that make it possible to perform calculations for rocks having intermediate values of basic physical and mechanical properties.

To assess the energy transfer, the displacement amplitude of the explosive-rock interface and the speed of the displacement of this interface were determined, while the rest of the parameters were calculated on the basis of the hydrodynamic theory of shock wave propagation.

The rock samples were presented by the cores with a diameter of 53-66 mm. The holes with a diameter of 6 mm and with a depth of 75 mm were bored in the samples.

The measurement of the displacement of the explosive-rock interface was carried out by flash radiography, which makes it possible to get a fairly clear picture of the interface for the set time period, based on the difference in the X-ray absorption by the detonation products and the rock. If we know the geometrical coefficient of the displacement increase, it is possible to determine the displacement of the rock in the middle part of the charge. The flash radiography was carried out using two X-ray tubes at the moments of 50.7 + 2.5 µs and 70.1 + 2.5 µs after the initiation of the charge.

The initial rate of the displacement of the explosive-rock interface and the rate of the detonation of an explosive in a rock were identified using the identical samples by the electromagnetic method.

Ionization detectors, positioned at the ends of the charge, were used to measure the rate of detonation. The velocity of a shock wave in the rocks was determined using flat samples of rocks on the basis of the distance and time of the wave propagation between the sensors, installed under the ends of the pressure charge and on the bottom side of the plate, cut out from the studied rock.

In the course of the study, the authors come to the conclusion that with the increase of the rate of detonation, i.e. the pressure on the explosive-rock interface, dissipative energy losses also increase. The shock compressibility of the rock most accurately reflects the behavior of a rock under dynamic loading. As dynamic compressibility is closely related to the porosity of a rock, it is obvious that the higher the porosity of the rock, the more are dissipative losses, which can be attributed to the higher specific heat capacity of the air, contained in the pore space of the rock.

The works (Vinogradov, 1976; Zhurov, 2007) show the dependence of energy, transferred by the compressive wave, on the adjusted distance, and make it obvious that the most considerable dissipation of energy takes place in the near-field of an explosion, which indicates significant energy consumption for irreversible processes, determined both by the result of the inelastic compression in the wave front and the plastic flow of the medium behind the wave front. This implies a very important practical conclusion that in order to improve the blasting efficiency it is necessary to reduce the energy losses at the initial stage of the development of an explosion by accumulating the energy of explosion products in the charge cavity.

The studies (Torunov *et al.*, 2010; Menzhulin *et al.*, 2001) show that in order to improve the dynamics of the process of destruction and the efficiency of an explosion it is necessary to ensure the repeated impact of the products of an explosion of a blasthole charge on the destructed rock mass by changing the internal gas dynamics in the blasthole. This can be achieved by using blasthole charges of various designs, as well as by changing the modes and parameters of the initiation of a blasthole charge.

The works (Kovazhenkov, 1958; Eremenko *et al.*, 2002; Eremenko *et al.*, 2000) within the framework of the hydrodynamic theory of detonation provide an analytical description of a gas-dynamic process in detonation products in case of the multipoint initiation of a column blasthole charge, the results of which allow to conclude that multipoint initiation (with the number of points exceeding two) makes it possible to ensure a significant increase of the pressure in a shock wave and the optimal repetition frequency of secondary compression waves. As a result, the walls of the blasthole will be subjected to recurring cyclic loading, which will result in a complex interference pattern of the medium motion, determining the loading condition of the rock mass.

When a blasthole charge is regarded as a source of the wave field (Baum *et al.*, 1973; Eremenko *et al.*, 2001), it is generally assumed that instantaneous detonation takes place, wherein the condition of explosion products in the cavity is considered to be identical and only depends on the volume of the cavity. This assumption leads to a substantial simplification of the pattern of the wave field generated in a rock mass, not least because in the process of the interaction with the walls and bottom of a blasthole the pressure in the explosion products significantly exceeds the pressure at the peak of a detonation wave.

Moreover, the problem of description and evaluation of the source of the wave field becomes even more complicated, when the source of the wave field is represented by a blasthole charge of a complex design or a charge with a variable detonation mode. In this case, the process of the collision of detonation and shock waves, accompanied by the slowdown of the flows of detonation products, is a complex gas-dynamic problem, the solution of which would allow the purposeful control of the process of transferring the energy of an explosive to the environment by selecting an optimal design of a charge or an initiation mode.

For solving this problem we will use the method of numerical modelling of nonstationary detonation and gas-dynamic processes taking place during an explosion of a blasthole charge. Solving this problem is preceded by the study of the qualitative pattern of the process of transferring the energy of an explosive to the environment during the explosion of charges of various designs and with different parameters of initiation modes; to accomplish this, laboratory experiments were carried out, the methodology and results of which are provided below.

METHOD

The possibility of the implementation of theoretical developments in the field of nonstationary gas-dynamic processes in the context of the availability of advanced computing and information-processing equipment in the last decade have stimulated the emergence of works on numerical modelling of rock destruction processes.

The work of destruction of rocks by the action of an explosion is performed due to the internal energy of charge detonation products. Therefore, the condition of the explosion products contained in the explosion cavity significantly affects the work done by an explosion and determines not only the amount of shattered rock, but also the quality of the destruction.

The most part of the energy, released during the chemical transformation of an explosive, is absorbed in the near-field of an explosion, which considerably reduces the efficiency of blasting (Fortov, 2010; Kudryavtsev and Epstein, 2012; Andreev, 2007; Andreev, 2009).

To study the impact of an explosion on a rock mass in the near-field of an explosion, the parameters of the gas-dynamic impact of the pressure of explosion products and the parameters of the stress wave in a rock mass in the near-field of an explosion were calculated by numerical solution of a two-dimensional non-stationary problem. In the process of solution, detonation and gas-dynamic processes, as well as the processes of the discharge of detonation products through the blasthole mouth were considered, and the parameters of the flow were determined on the basis of calculations, including shock-wave and wave processes and dynamic loads on the blasthole walls.

The energy released in an explosion was considered with regard to the speed of detonation propagation along the length of a charge for various charge designs and methods of initiation. To simplify the calculations, blasthole walls were considered to be absolutely rigid. Under these assumptions, detonation and gas-dynamic processes in a blasthole can be described by a set of Euler equations, with adding a member, describing the energy release during the propagation of detonation, into the energy equation. The calculation system is complemented by the equation of the state of the medium (Brown and Thomas, 2000; Khristoforov, 2010; Torunov *et al.*, 2010; Bersen'ev, 1999; Borovikov and Vanyagin, 1976; Menzhulin *et al.*, 2012). As the mass of the air, contained in the blasthole, is insignificant as compared to the mass of detonation products, its impact can be neglected. In the blasthole mouth, the conditions of the free discharge of gas are set for the case of using an unstemmed charge.

The adopted statement of the problem makes it possible to evaluate the relative changes of gas-dynamic parameters during the explosion of charges, which are close in terms of the energy release of explosives.

On the basis of the described model, the parameters of gas-dynamic flows were calculated, including the parameters of dynamic loads on the wall of a blasthole during the explosion of charges having various designs and different initiation modes.

The shock wave, refracted into the rock on the charge-rock interface, in the process of further propagation in the rock quickly degenerates into a stress wave with an unsharp pattern of stress buildup to the maximum value. For the calculation of radial and tangential stresses we will use the technique of determining the components of a stress wave in the near-field of an explosion.

In the work (Shemyakin, 2007) it is theoretically shown that the nature of the stress wave amplitude attenuation is different for media with various friction and depends on the type of symmetry, which can be spherical or cylindrical.

Based on the above approach to calculating the parameters of a stress wave, a technique of numerical modelling was developed, which was used to calculate the parameters of gas-dynamic processes in a charge chamber during the explosion of blasthole charges.

The calculation was made for various charge designs (a charge with special stemming (Menzhulin *et al.*, 2012); a charge with sand-clay stemming; an unstemmed charge), wherein the charge was broken into four points located along its axis. A solid charge of granulite AS-8 was charged into a 2.5 m long blasthole; the length of the charge was 2 m. Direct and inverse initiation of the charge was considered. It should be noted that inverse initiation is most widely used in roadway construction.

Calculations show that at the moment of the reflection of a wave from the bottom of the blasthole in case of direct initiation, the pressure level in it quickly drops to the quasi-static in the bottom part of the blasthole, while in the mouth part the pressure remains somewhat lower than in case of inverse initiation. Later the wave processes attenuate quickly enough for both initiation patterns.

The violation of the unidimensionality of wave propagation is observed only near the mouth of the blasthole due to the discharge, but it almost does not affect the flow inside the blasthole.

In case of the decrease of the density of various explosives, the pattern of the discharge is preserved, while the overall pressure level is reduced. For granulite AS-8, in case of the change in the density, all the basic regularities of the discharge are preserved; the parameters in the front of a denotation wave and a strong shock wave are higher because of the higher value of the specific heat ratio, but as explosion heat is lower, the decrease of the pressure in the blasthole and on its walls occurs faster.

Figure 1 shows some of the results of the calculation of gas-dynamic parameters in the charge chamber of a blasthole in the form of a pressure-time curve for the pressure on the wall of a blasthole. This calculation was made for a charge with special stemming and with an inverse initiation mode.

The analysis of all the results shows that the qualitative pattern of gas-dynamic processes is changed in case of the presence of stemming in a blasthole. After the interaction of a detonation wave with clay stemming, the parameters of a reflected shock wave, propagating towards the bottom of the well, are comparable with the parameters of a detonation wave. The pressure applied to the end of the stemming insignificantly differs from the pressure on the wall of a blasthole in the vicinity of the stemming and sharply decreases at the output, as the stemming is discharged. A shock wave is repeatedly reflected from the bottom of the blasthole and from the stemming, wherein the amplitude of the wave slowly decreases, and the quasi-static pressure level in the blasthole slightly increases.

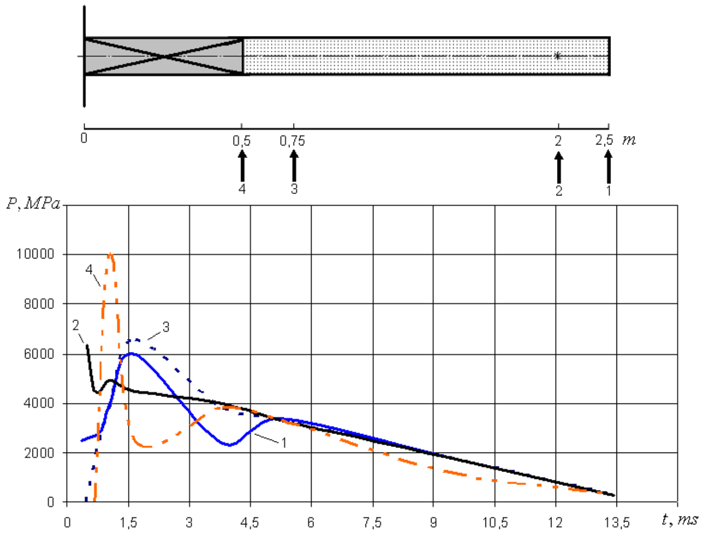

Figure 1: Design of a charge and a pressure-time curve for the pressure on the wall of a blasthole.

Figure 2 shows the resultant action of the pressure of gaseous explosion products on the wall of a blasthole depending on the charge design. 1 – a charge with special stemming; 2 – a charge with sand-clay stemming; 3 – an unstemmed charge; 4 – complete blocking of detonation products.

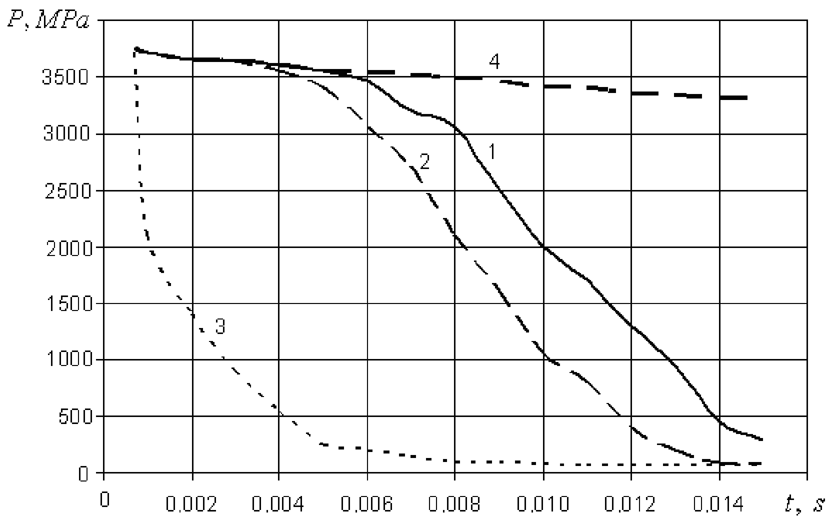

Figure 2: A curve of the resultant action of the pressure of gaseous explosion products on the wall of a blasthole depending on the charge design.

The pressure-time dependence for the average pressure on the wall of a blasthole (curve 1 in Figure 2) shows that the reduction of pressure in case of using packed stemming is insignificant, and an intense decrease of pressure is observed only in case of the explosion of an unstemmed charge (curve 3). This is confirmed by the shape of curves in case of using different types of stemming. As a limit case we considered the case of complete blocking of detonation products, when a rigid wall is provided instead of stemming. The difference between the curve 4, corresponding to the limit case, and the curves 1 and 2 in Figure 2 characterizes the reduction of the pressure in the explosion cavity due to the discharge of the detonation products through the blasthole channel with the outburst of the stemming material. At the final stage, after the full discharge of the stemming material and a part of detonation products from the blasthole, intense wave processes in the explosion cavity decay.

It should also be noted that the change of the charge length at a constant diameter of the blasthole, or the change of the detonation speed at the constant ratio of the charge diameter to the blasthole length, results only in the change of the time characteristics, while the qualitative characteristics of the development of gas-dynamic processes remain unchanged.

On the basis of the numerical results obtained for the pressure in the charge cavity in case of various charge designs, the authors calculated the explosive pulses (Figure 3), which determine the degree of destruction of a rock mass. In general terms, an explosive pulse is a pressure-time function for the pressure in the front of a detonation wave, summarized for the time of the impact of detonation products on a rock mass.

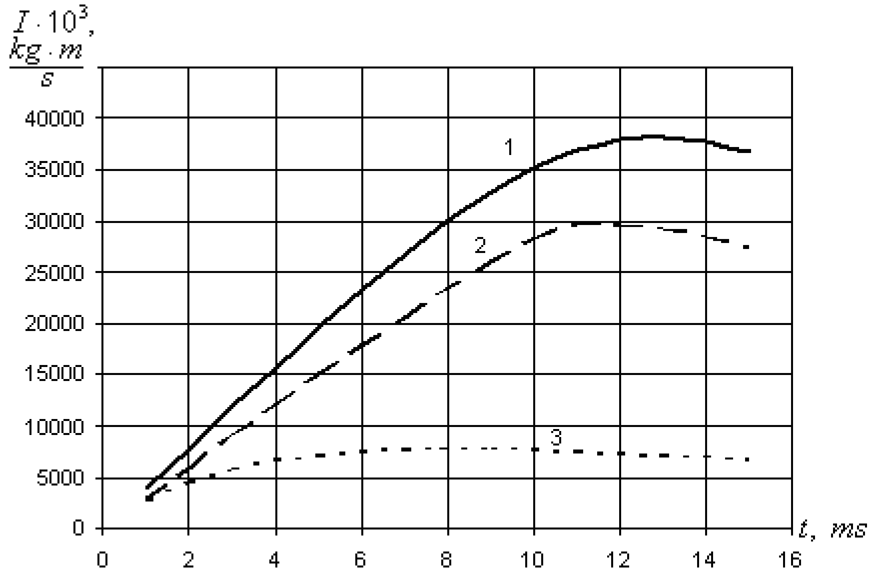

Figure 3: Curve of an explosive impulse against time ana charge design.

The results show that end time of the active action of an explosive pulse amounts to 13 ms for charges with special stemming, 11 ms for sand-clay stemming and 9 ms for unstemmed charges.

Thus, if we introduce the coefficient of the dynamic impact of an explosive pulse on the mass of an unstemmed charge and take it to be equal to 1, this coefficient will be equal to 1.44 for charges with special stemming and 1.22 for charges with sand clay stemming.

The obtained coefficients of the impact of an explosive pulse make it possible to adjust the calculations of blasting ratio for various charge designs.

RESULTS

The analysis of the gas-dynamic processes taking place in the explosion cavity of a blasthole charge made it possible to reveal the dependence of the change of the pressure applied to the walls of the explosion chamber on the type of the used stemming material, which offers an opportunity of adjusting the loading of the rock mass during blasting operations by selecting the design parameters of blasthole charges. The analytical study of the gas-dynamic processes in the explosion cavity shows that the change of the charge length at a constant diameter of the blasthole, or the change of the detonation speed at the constant ratio of the charge diameter to the blasthole length, results only in the change of the time characteristics of these processes, while the qualitative characteristics remain unchanged.

Numerical modelling made it possible to determine the time of the impact of the detonation products on the rock mass at the quasi-static stage. The values of the explosive pulse for various charge designes were obtained; these values amount to 9 ms, 11 ms and 13 ms, respectively, for unstemmed charges, charges with sand-clay stemming and charges with graded stemming.

DISCUSSION

The mechanism of the destruction of rocks by blasting an explosive charge is rather complicated, since the process of destruction occurs within a very short time at rather high values of dynamic loads. Therefore, a single view on the problem of the destruction of rocks by an explosion hasn't been developed thus far. Many scientists attempted to reveal the physical essence of the process of deformation of the medium by the action of an explosion, the energy parameters of this process and the methods of its management. However, the results of the studies are varied and often contradictory.

The conducted studies differ in the system of the approach to the problem of the action of an explosion in a rock mass. Basically, there are three directions, based on hydrodynamics, wave theory and the hypothesis of the two components of the stress field.

An explosion is a process of high-speed dynamic loading of rocks. However, the nature of the loading of rocks during an explosion and the resulting deformation of a rock mass are treated differently. From the standpoint of the concepts of hydrodynamics and the theory of shock waves, the process of explosive dynamic loading is regarded as a single peak pressure pulse, acting within a certain period of time. The concept of the two components of the stress field implies the existence of the impact load in the beginning of the process, followed by the quasi-static load, which is slowly varying with time. The nature of loading and the accepted criteria of destruction are different in each of these cases.

Currently, many scientists believe that the process of transferring the energy of an explosion to the environment cannot be confined within the limits of the impact wave. It is assumed that the detonation of an explosive has a pulsing nature. Seismographic and acoustic equipment, installed at various distances from an explosion, captures not an isolated peak pulse of a shock wave, but a cycle of harmonic sinusoidal oscillations, wherein seismometers initially record a series of low-amplitude oscillations, followed by oscillations with a higher amplitude, rather than vice versa. In such a case, loading of rocks during an explosion is a dynamic and pulsating oscillatory process with a relatively small number of active loading cycles. The mechanism of the destruction of rocks by an explosion can be considered from the perspective of low-cyclic fatigue of rocks, having a relatively low tensile strength. On the basis of these studies, A.A. Vovk (Vovk, 1985) proposed a hypothesis of the two components of the stress field in the vicinity of the charge: high-frequency, corresponding to the front of the shock wave, and long-period, resulting from the quasi-statics load caused by the action of the detonation products of an explosive.

The above brief analysis of the basic concepts of the mechanism of rock destruction shows that these concepts vary greatly depending on the original factor of the destruction of rocks by an explosion, assumed by the authors.

In underground mining, the dynamic methods of roadway construction are mostly used, based on the use of explosives in trimming blastholes or wells.

Controlled blasting is a widely used method of breaking rocks in a preset direction, based on the use of explosives.

Controlled blasting is used for separating blocks from a rock mass, roadway construction, construction of underground chambers, roadway excavations and for extraction.

Controlled blasting is a special way of implementing blasting operations, providing for the creation of local stresses, concentrated along the plane of the proposed split of a rock mass. This ensures obtaining smooth crack-free surfaces with a specified contour.

The advantages of the technology of drilling and blasting operations with the use of controlled blasting consist in the improvement of the stability and strength of the peripheral rock mass due to the decrease of jointing in the process of blasting explosive charges.

In case of using the method of shielding controlled blasting, the presence of a thin split ensures the reflection of explosion waves from relieving charges, prevents the propagation of cracks into the peripheral rock mass and contributes to the improvement of blasting quality.

The analysis of the long-term experience of using the methods of controlled blasting shows that these methods always ensure the improvement of the stable state of free faces of rock masses, even unstable ones.

In the world practice, a wide experience of the construction of roadways of various purpose in underground conditions with the use of the methods of controlled blasting has been accumulated.

When using the method of post-splitting, the trimming charges after the explosion break off rocks to the excavation formed in the stope by the explosion of main charges of a set of blastholes. Post-splitting may be implemented in two ways: the explosion of charges in blastholes bored in the plane of the roadway contour, and the explosion of charges in short blastholes bored after the removal of rock perpendicular to the contour. It is considered that in the second case the ends of short charges cause minimal deformations in the peripheral rock mass, as the stress caused by an explosion is insignificant in the axial direction and propagates in the radial direction. However, the method of perpendicular blastholes is used relatively infrequently, and only in large-bore roadways.

In case of using the method of post-splitting, trimming charges of a smaller diameter are usually taken, or they are charged with explosives having a lower detonation speed; explosive cartridges, the diameter of which is smaller than the diameter of a blasthole, are also used.

At low concentrations of the explosive in blastholes and relatively short distances between them, the crack caused by an explosion passes only through blastholes and does not propagate in other directions, in particular, to the peripheral part, where the fracture resistance of rocks is much higher than that of exposed surface.

When using the method of pre-splitting, in contrast to post-splitting, trimming charges are exploded first. The explosion of these charges results in the formation of a main crack or split between trimming blastholes.

The main purpose of such pre-splitting is the formation of a shield, protecting the peripheral rock mass from the destruction by shock or seismic waves, formed in the course of ground breaking.

In the process of roadway construction, the method of pre-splitting is used relatively infrequently.

The effectiveness of the formation of a shielding split depends on the correct selection of an optimal distance between trimming charges in a line and the charge mass, with regard to the specific physical and mechanical properties of rocks and geomechanical conditions in the area of the delineated excavation. It should be noted that in case of using the method of controlled pre-blasting (or pre-splitting of a rock mass) the impact of the above factors is more significant than in case of using the method of post-splitting.

The method of pre-splitting is implemented with the use of various charge designs, ensuring the directional action of explosion waves.

The method of controlled explosion with pre-splitting ensures the stability of rocks in the peripheral part of a rock mass. Using this method in roadway construction ensures a longer life cycle of tunnels for the admission of water to the power plant turbines, supports of high-altitude dams of hydroelectric power plants in rocky shores, various large-volume chamber excavations in hard rocks, etc.

The analysis of domestic and foreign literature and the operation of the mining enterprises showed that the parameters of controlled blasting are determined using empirical formulas, confirmed by experimental explosions. One of the main parameters of controlled blasting is the distance between the charges in the contour line. The formulas for determining this distance, known from the literature, have a limited range of use in the conditions of underground mining, because they don't include values, describing the gas-dynamic impact of the pressure of explosion products and the parameters of a stress wave in a rock mass in the near-field of an explosion.

CONCLUSION

On the basis of numerical modelling, the authors determined the time of the impact of detonation products on the rock mass at the quasi-static stage. The values of the explosive pulse were obtained for various charge designs.

It should be noted that this paper dealt with only some of the designs of explosive charges with different parameters of initiation modes. Therefore, there is the need for further theoretical and practical study of the impact of the charge design on the distribution of dynamic processes in a charge cavity.

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