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CONTROLLING THE PROCESS OF EXPLOSIVE DESTRUCTION OF ROCKS IN ORDER TO MINIMIZE DUST FORMATION AND IMPROVE QUALITY OF ROCK MASS

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На основі адаптованої моделі Ляхова Г. М. встановлено закономірність проходження хвиль тиску при підриванні гірських порід від акустичної жорсткості заповнювача проміжку між зарядом та стінкою свердловини та його величини. Визначено, що зі збільшенням акустичної жорсткості розчину, який пропонується використовувати як заповнювач проміжку між зарядом та свердловиною, пік тиску у ближній до заряду зоні зменшується. Окрім того збільшується ширина амплітуди хвилі тиску. Зі збільшенням величини проміжку за рахунок застосування зменшених діаметрів зарядів ефект зниження обсягу пилоутворення посилюється. Встановлено закономірності проходження хвиль тиску від акустичної жорсткості заповнювача проміжку між зарядом та стінкою свердловини, а також його величини для різних типів скельних порід. Зокрема для базальту, діабазу, граніту, габро та вапняку. Визначено, що розчини з більшою акустичною жорсткістю дозволять зменшити обсяг пилоутворення та підвищити однорідність фракційного складу гірської маси. Це можливо за рахунок зменшення амплітуди хвиль тиску на межі розподілу середовищ та збільшення ширини амплітуди у будь-якій скельній породі. Зокрема заповнення проміжку водним розчином сульфату заліза (III) дозволяє зменшити амплітуду хвиль тиску на 20 %. Результати досліджень є важливими, так як дозволяють управляти процесом вибухового руйнування скельних порід. Таке управління може здійснюватися за рахунок зміни акустичної жорсткості заповнювача проміжку між зарядом і свердловиною і зміни його величини. Регуляція даних параметрів не погіршить результати вибуху, як наприклад зменшення витрати вибухової речовини, або зменшення діаметру заряду. А навпаки забезпечить більш рівномірне поширення хвиль тиску у масиві і тим самим дозволить зменшити не лише навантаження на навколишнє середовище, а й собівартість готової продукції.

Ключові слова: скельні породи, процес пилоутворення, вибухове руйнування, зона переподрібнення, фракційний склад гірської маси

1. Introduction

At present, a prevailing technique in the development of mineral resources is the open technique, which is characterized as the most economical and efficient. It is the development of mineral resources using open technique that causes the greatest damage to the components of the environment. Specifically, pollution with the micro dispersed dust and harmful gases, which depends on both natural factors and the technology for conducting mining operations [1].

From 24 to 48 serial explosions are performed at the quarries of major mining and metallurgical enterprises of Ukraine annually. At the average productivity of each at 300–800 thousand m^3 of rock mass, the volume of a dust-gas cloud, which is discharged into the atmosphere, reaches 10–15 thousand m^3, with the concentration of dust amounting to 700–4,150 kg/m^3 [2]. A dust-gas cloud, which forms during explosive works, pollute the atmosphere not only of quarries and industrial sites, but the residential areas adjacent to them as well [3]. That impacts the health of people living at adjacent areas [4]. Thus, explosions that use 1,000 tons of explosive substances (ES) pollute around 40 million m^3 of atmospheric air that exceeds MPC by tens of times. In this case, the range of its distribution reaches 15 km, and even more [3]. Therefore, increasing the level of environmental safety during mass explosions in the quarries by improving the operation technology is an important scientific and practical task.

2. Literature review and problem statement

At present, reduction of gas-dust release during mass explosions is achieved by technological, technical, and organizational measures [5]. Most commonly used are the technological measures that imply improvement of the design of a charge and tamping. Design of the charge is improved by adding to the charges of ES slaked lime or soda, by reducing the diameter of the charge, by separating the column of the charge by air and inert intervals, by decreasing the magnitude of re-drilling [6]. Special attention is paid to the choice of explosives and detonation techniques. The effectiveness of their influence on the results of explosion, particularly on the area of re-shredding, is described in paper [7]. Design of the tamping can be improved by using a hydrotamping, a tamping with water solution of SAS [5]. However, such measures, when applied separately, do not yield the desired effect. Adding to the charges of ES slaked lime or soda reduces the amount of harmful gases that form at blasting. In this case, the issue of dust formation and quality of the rock mass remains to be studied.

Research results of the influence of the diameter of a borehole charge on the contact area between an explosive and the rock that is destroyed, as well as on the output of small factions, are reported in paper [8]. The authors proved that at a constant specific consumption of an explosive reducing the diameter of wells leads to an increase in the area of contact between the explosives and rock. That contributes to improving the conditions for locking the products of detonation in wells and to the improved efficiency of explosion. In this case, the expanding area of a wells network and the corresponding reduction of specific consumption of an explosive create conditions for reducing the yield of small fractions [8]. However, reducing the diameter of the charge helps reduce a re-shredding zone but does not address the issue of the release of harmful gases and the homogeneity of fractional composition.

Author of [9] developed a design of the borehole charge with an air cavity in the bottom part of the borehole. Its application makes it possible to reduce specific consumption of ES to 0.513 kg/m^3 of the blasted rock mass. However, dividing the charge column by air and inert intervals allows only the more efficient use of the blast energy, while an increase in the volume of the zone of controlled shredding was not scientifically substantiated in a given paper.

To reduce the re-shredding zone and dust emission, it is more appropriate to design a charge with air or water gaps between the charge and the wall of the well. The existence of a radial air gap leads to a decrease in the magnitude of an impact wave amplitude, reducing the initial peak pressure and increasing the width of the amplitude (Fig. 1). That makes it possible to increase the pulse duration of the impact wave influence on the environment and leads to a reduction in energy costs for the dissipative loss. The result of the use of such designs is the greatly increased efficiency coefficient of the blast energy [10]. However, this effect could potentially be reinforced by the scientifically substantiated choice of the filler for a gap between the charge and the wall of the well.

Reducing the magnitude of re-drilling makes it possible to reduce the amount of dust formation by reducing the action of an explosion at the area of re-drilling, however, it contributes to the creation of steps along the bottom of the ledge. The technology of explosion, described in [6], employed well charges without re-drilling, at the bottom of which, at the level of the sole of the ledge, air "cushions" form, designated by the authors as "Power Deck". Prior to charging, "Power Deck" is inserted into the well; its container is filled in advance with drill cuttings to increase the weight of the structure to enable its smooth fall to the bottom of the well [6]. According to the authors, the effect of the air bag of "Power "Deck" is achieved by a total action of the impact wave energy and a piston action of blast products to the borehole. The result of the proposed solution implementation is that the authors partially resolved the issue of thresholds and re-shredded fractions. However, labor intensity and high cost of the charging process prevented its wide application in rock quarries.

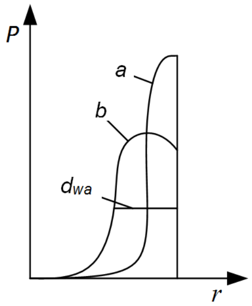

Fig. 1. Amplitude of an impact wave: a — without a radial air gap; b — with an air radial gap; d_{wa} — width of amplitude

The transition from TNT containing explosives to simple water-emulsion ones with a null, or close to it, oxygen balance [11] made it possible to reduce the amount and list of harmful gases. However, it is almost impossible to achieve the homogeneity of the fractional composition with such a replacement.

Improvement of location parameters of the downhole charges, taking into account the properties of rocks, made it possible to increase the efficiency of processing a ledge by considering the structural-texture features in an array of rocks [12]. However, the qualitative composition of the blasted mountain mass was not considered in the paper. Article [13] pays attention to the influence of geometry of a downhole charges network on the fragmentation of the rock mass. However, these studies do not take into account the impact of a peak pressure in the region, close to the charge, on the yield of re-shredded fractions.

Technical measures for reducing gas-dust release at mass explosions include the spraying of blocks before a blast with aqueous solutions of SAS, spraying a zone of dust discharge from a dust-gas cloud, and constructing the hydro curtains [5]. They also use special decks in wells to enhance the quality of fractional composition of rock mass and to reduce theh level of vibration [14]. However, such measures are aimed at minimizing the effects only, rather than the elimination of their causes.

Organizational measures only make it possible to shorten the time of dispersing a dust-gas cloud by carrying out mass explosions over a period of maximum wind activity with respect to the wind rose for a specific region [3].

Authors of [15] express their opinion on that it is advisable to apply a comprehensive approach to address problematic issues concerning environmental safety during blasting operations in quarries.

Summing up the analysis we conducted, it is worth noting that the developed measures have not been widely applied in rock quarries. The main reasons are the complexity, labor intensity, and high cost, on the one hand, and their little effect on the explosion results (fractional composition of a rock mass and the volume of dust formation), on the other hand. Given this, the rock quarries still suffer, in the production of crushed stone, from a problem of the high percentage of nonconditional fractions of the rock mass in the fraction composition. Particularly, the re-shredded ones, which, in contrast to fractions larger than the conditioned, cannot be brought to the conditioned size. It is the re-shredded fraction that is the source of dust formation in the quarries and that takes the primary share in the waste of mining production. It has not been established up to now which design parameters of the charge could be changed without compromising the efficiency of shredding and which, at the same time, have a significant effect on the dimensions of a re-shredding zone. The most appropriate at this stage is considered to be the application of an interval between the charge and the wall of the well, filled with air or water. It was proved that the water, acting as a damper, would reduce the size of the zone of re-shredding and it has a greater effect than the air. However, until now, no impact of the characteristics and properties of a filler for a gap between the charge and the wall of the well was determined, nor the effect of its magnitude on the results of destroying the rock by explosion. The process of rock destruction is, to a greater extent, uncontrollable.

3. The aim and objectives of the study

The aim of this research is to control the process of explosive destruction of rocks in order to reduce dust formation and improve the quality of the blasted rock mass.

To accomplish the aim, the following tasks have been set:

– to establish the dependences in the passage of pressure waves at the explosion of a borehole charge on the spatial coordinate (a distance to the source of explosion), the magnitude of the gap between the charge and the well, and characteristics of the gap filler based on adapted model by G. M. Lyakhov;

– to substantiate a rational magnitude of the gap between the charge and the well and the characteristics of the filler;

– to substantiate the feasibility of the proposed approach for different types of rock.

4. Materials and methods to study the process of explosive destruction of rocks

When modeling, rock is considered to be a three-component environment, which consists of the gas, liquid, and solid components. A special case is the solid component only. Under the action of a dynamic load, in the microvolume of rock, the component is exposed to pressure P and it moves at a conditional speed U, while the deformation of the component under the influence of pressure P is governed by the same laws that act in the free state. The following designations are introduced to the equation of state of such an environment: α_i is the content of components by volume; ρ_{i0} is the density; V_{i0} is their specific volume; c_{i0} is the speed of sound in the components at atmospheric pressure P_0; i is the number of the component (1 – air, 2 – liquid, 3 – solid particles), γ_i are the isentropic coefficients according to the Tait equation. At a pressure of $P=P_0$, the density of environment ρ_0 and specific volume V_0 are determined from formulae:

$$\rho_0=\frac{1}{V_0}=\sum_{i=1}^{3}\alpha_i\rho_{i0},\quad \sum_{i=1}^{3}\alpha_i=1. \tag{1}$$

At pressure P, we shall denote component parameters as V_i, ρ_i, c_i; and those of the environment in general V and ρ. Density of the environment at pressure P is composed of the initial density ρ_0 and the terms predetermined by the compression of each component, that is,

$$\frac{\rho_0}{\rho}=\frac{V}{V_0}=\sum_{i=1}^{3}\alpha_i\frac{V_i}{V_{i0}}. \tag{2}$$

If we substitute in a given expression the value for specific volume of the components at pressure P, we then obtain the equation of compression of the nonlinear elastic multicomponent environment in the form

$$\frac{\rho_0}{\rho}=\frac{V}{V_0}=\sum_{i=1}^{3}\alpha_i\left[\frac{\gamma_i\left(P-P_0\right)}{\rho_{i0}c_{i0}^2}+1\right]^{-\chi_i}, \tag{3}$$

where $\chi_i=1/\gamma_i$.

The advantage of this model is its simplicity, the possibility to represent the dependence of a sound wave speed on pressure in the form of simple correlations. In a given case, the model is adapted for the two-component environment, through which the pressure waves pass at explosion. The model was thoroughly verified in practice and showed a high convergence between theoretical and experimental results. The speed of sound at pressure P is derived from condition $c=(dP/ds)^{1/2}$ and takes the form

$$c=\frac{\sum_{i=1}^{3}\alpha_i\left[\frac{\gamma_i\left(P-P_0\right)}{\rho_{i0}c_{i0}^2}+1\right]^{-\chi_i}}{\left\{\rho_0\sum_{i=1}^{3}\frac{\alpha_i}{\rho_{i0}c_{i0}^2}\left[\frac{\gamma_i\left(P-P_0\right)}{\rho_{i0}c_{i0}^2}+1\right]^{-\chi_i-1}\right\}^{\frac{1}{2}}}. \tag{4}$$

The movement of a two-layer environment that consists of rock and a damping layer, for the case of propagation of cylindrical waves, is described by the system of equations in the Euler's coordinates for each layer [16].

$$\frac{\partial}{\partial t}(\rho U)+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho U^2+P\right)\right]-\frac{1}{r}P=0;$$

$$\frac{\partial\rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left[r(\rho U)\right]=0, \tag{5}$$

where r is the spatial coordinate, t is the time coordinate, U is velocity, ρ is density, P is pressure.

Accordingly, the equations of state are written for each layer:

$$F(P,\rho)=\sum_{i=1}^{3}\alpha_i\left[\frac{\gamma_i(P-P_0)}{\rho_{i0}c_{i0}^2}+1\right]^{-1/\gamma_i}-\frac{\rho_0}{\rho}=0. \tag{6}$$

Next, we consider the non-stationary behavior of a two-layer layer medium at certain initial conditions. It is assumed that the load $P(t)|_{r=r0}$ is applied to the boundary of a certain cylindrical cavity of radius $r=r_0$ (for the case of cylindrical symmetry) (Fig. 2).

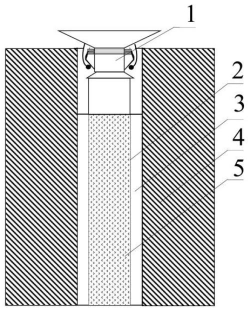

Fig. 2. Schematic representation of the two-layer environment "gap filler – rock": 1 – device that feeds a plastic hose; 2 – plastic hose; 3 – gap between the charge and the wall of the well; 4 – rock; 5 – explosive substance

The algorithm for solving the problem on the behavior of a two-layer medium under loading the cylindrical cavity with non-stationary load $P(t)|_{r=r0}$, equations (5), (6), is based on the application of a finite-difference scheme the predictor-corrector by McCormack [17, 18].

At a step of the predictor, difference equations for the case of cylindrical symmetry take the form:

$$\tilde{\rho}_k = \rho_k^n - \frac{\tau}{r_k}\left[\frac{(r\rho^n V^n)_{k+1} - (r\rho^n V^n)_k}{\Delta r}\right]; \tag{7}$$

$$(\tilde{\rho}\tilde{V})_k = (\rho^n V^n)_k -$$
$$-\frac{\tau}{r_k}\left\{\frac{[r\rho(V^2+P)^n]_{k+1} - [r(\rho V^2+P)^n]}{\Delta r} - P_k^n\right\};$$

$$F(\tilde{P}_k, \tilde{\rho}_k) = 0. \tag{8}$$

At a step of the corrector, equations are recorded as follows:

$$\rho_k^{n+1} = 0{,}5\left\{\rho_k^n + \tilde{\rho}_k - \frac{\tau}{r_k}\left[\frac{(r\tilde{\rho}\tilde{V})_k - (r\tilde{\rho}\tilde{V})_{k-1}]}{\Delta r}\right]\right\}; \tag{9}$$

$$(\rho V)_k^{n+1} = 0{,}5\Big\{(\rho^n V^n)_k + (\tilde{\rho}^n \tilde{V}^n)_k \; -$$
$$-\frac{\tau}{r_k}\left[\frac{[r(\tilde{\rho}\tilde{V}^2+\tilde{P})^n]_k - [r(\tilde{\rho}\tilde{V}^2+\tilde{P})^n]_{k-1}}{\Delta r} - \tilde{P}_k\right]\Big\};$$

$$F(P_k^{n+1}, \rho_k^{n+1}) = 0. \tag{10}$$

To find the desired magnitudes at the surface of cylindrical cavity, we apply the following difference equations:

$$\tilde{\rho}_0 = \rho_0^n -$$
$$-\frac{\tau}{r_0}\left[\frac{-3r_0(\rho_0^n U_0^n) + 4r_1(\rho_1^n U_1^n) - r_2(\rho_2^n U_2^n)}{2\Delta r}\right]; \tag{11}$$

$$\left(\tilde{\rho}\tilde{U}\right)_0 = \left(\rho^n U^n\right)_0 - \frac{\tau}{r_0}\times$$
$$\times\left[\frac{-3r_0(\rho_0^n U_0^n + P_0^n) + 4r_1(\rho_1^n U_1^n + P_1^n) - r_2(\rho_2^n U_2^n + P_2^n)}{2\Delta r} - P_0^n\right];$$

$$F(\tilde{P}_0, \tilde{\rho}_0) = 0. \tag{12}$$

At a step of the corrector, equations at the boundary of the cavity take the form

$$\rho_0^{n+1} = \tilde{\rho}_0 - \frac{\tau}{r_0}\times$$
$$\times\left[\frac{-3r_0(\tilde{\rho}_0\tilde{U}_0) + 4r_1(\tilde{\rho}_1\tilde{U}_1) - r_2(\tilde{\rho}_2\tilde{U}_2)}{2\Delta r}\right]; \tag{13}$$

$$\left(\rho U\right)_0^{n+1} = \left(\tilde{\rho}\tilde{U}\right)_0 - \frac{\tau}{r_0}\times$$
$$\times\left[\frac{-3r_0(\tilde{\rho}_0\tilde{U}_0 + \tilde{P}_0) + 4r_1(\tilde{\rho}_1\tilde{U}_1 + \tilde{P}_1) - r_2(\tilde{\rho}_2\tilde{U}_2 + \tilde{P}_2)}{2\Delta r} - \tilde{P}_0\right];$$

$$F(P_0^{n+1}{}_0, \rho_0^{n+1}) = 0. \tag{14}$$

Given that the McCormack difference scheme is explicit, we used the condition for numerical stability for calculations:

$$\left(|U| + c\right)\tau / \Delta r < 1, \tag{15}$$

where magnitude c corresponds to the local speed of sound in the examined environments (4).

5. Results of research into studying the process of explosive destruction of rocks

We consider a cylindrical cavity of radius $r=R$ in the mountain rock – equations (5), (6). The statement of the problem is schematically shown in Fig. 2. It is assumed that the load $P(R,t)$ is applied to the inner boundary of the cavity; it takes the form:

$$P(R,t) = A\sin\frac{\pi t}{T}[\eta(t) - \eta(t-T)], \tag{16}$$

where $A=10^7$ Pa; $T=50\cdot10^{-6}$ s; $\eta(t)$ is the Heaviside function.

The first layer (a gap between the charge and the well) is within the area of $R \le r \le 2R$, the second layer (rock) – $2R \le r \le \infty$. Parameters of the equation of state (3) are variable.

To calculate the magnitude of pressure depending on the magnitude of the gap and characteristics of the filler, we used the following data: $\gamma_1=1{,}4$; $\gamma_2=7$; $\gamma_3=4$ and data from Table 1. To obtain the estimation data on our study, we developed a software written in the programming language FORTRAN. Processing of the derived results and construction of dependence charts was carried out using the package Microsoft Office Excel.

Fig. 3 shows results of numerical calculation of pressure at a change in the spatial coordinate. Particularly, it demonstrates the dependence of pressure P wave propagation on spatial coordinate r, depending on acoustic rigidity of the gap filler between the charge and the wall of the well for fillers 1, 4, and 7. Calculation is performed for granite based on data from Table 1.

The results of analysis of Fig. 3 show that an increase in the acoustic rigidity of the solution that is proposed to be used as a gap filler between a charge and the well leads to a decrease in the peak pressure in the zone close to the charge.

A maximum of this reduction can be achieved when using a dense solution – filler 1; in this case, the aqueous solution of iron (III) sulphate, whose characteristics are: ρ_n= =1,798 kg/m^3 and c=2,712 m/s. Thus, while applying it, the maximum pressure in the zone close to the charge, which is the main source of dust formation, is 8.19×10^6 Pa. At the same time, when using water (filler 2), which is commonly used, this pressure is 9.91×10^6 Pa, nearly 20 % larger. As a conclusion, it is worth noting that the solutions with a larger acoustic rigidity will make it possible to decrease the amount of dust formation and increase the uniformity of the fractional composition of rocks. This is possible due to a decrease in the amplitude of pressure waves at the boundary of the media “gap filler – rock” and an increase in the width of the amplitude (Fig. 3). In addition, such an approach makes it possible to increase the level of resource-saving. Particularly, that helps reduce losses related to the re-shredded fractions, which are a waste of the mining production and are disposed of in the dumps that produce a negative impact on the environment due to dust.

Table 1

Initial data to establish the dependence of pressure waves propagation om the spatial coordinate

Well diameter, mm	Charge diameter, mm	Rock characteristics		Characteristics of the gap filler between the charge and the wall of the well		
		Density, kg/m^3	Speed of sound, m/s	No.	Density, kg/m^3	Speed of sound, m/s
250	160	2,650	4,500	1	1,798	2,712
				2	1,449	1,985
				3	1,181	1,600
				4	1,000	1,450
				5	880	1,082
				6	800	992.09
				7	720	985.52

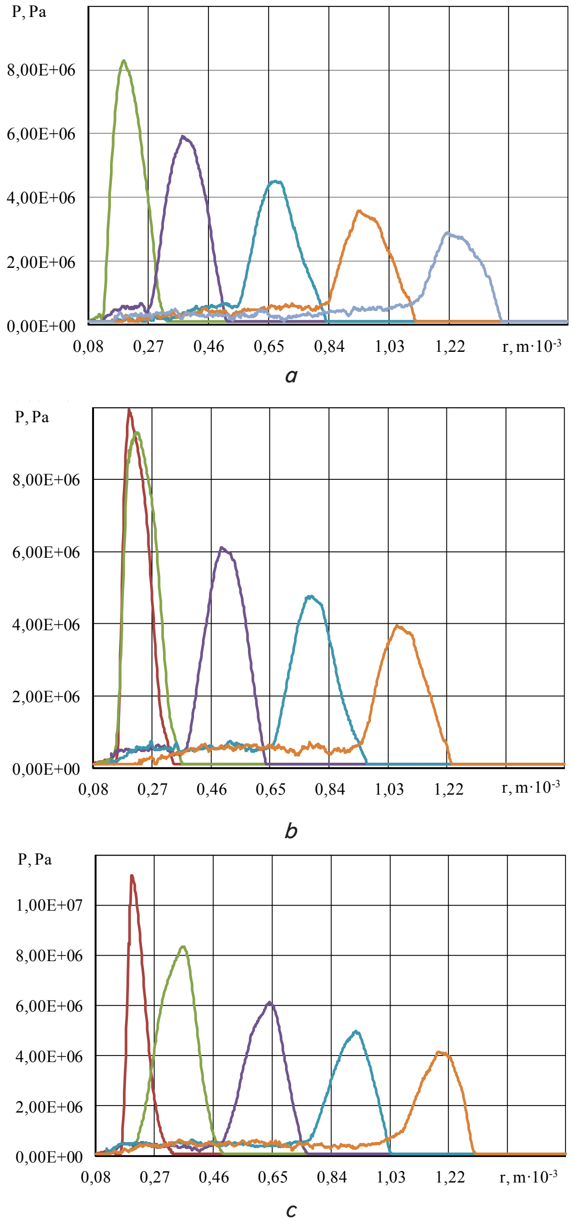

Fig. 3. Dependence of pressure waves propagation on a change in the spatial coordinate for different types of the gap filler between the charge and the walls of the well: *a* – filler 1; *b* – filler 4; *c* – filler 7

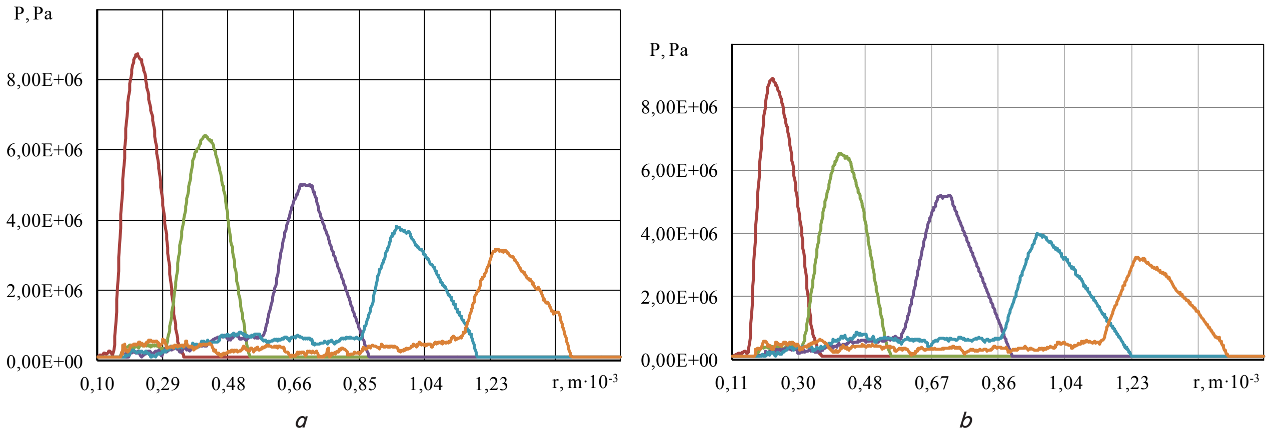

Fig. 4. Dependence of pressure waves propagation on a change in the spatial coordinate in granites when using the aqueous solution of iron (III) sulphate for the following diameters of charges: *a* – 200 mm, *b* – 220 mm

Similar calculations were performed using the aqueous solution of iron (III) sulphate for the diameters of the charges of 200 and 220 mm in order to establish the rational magnitude of the gap between the charge and the wall of the well at the same initial data (Fig. 4). Fig. 3 and Fig. 4 show that the lowest peak of pressure is observed at a diameter of the charge of 160 mm and a diameter of the well of 250 mm. That suggests that an increase in the magnitude of the gap by applying smaller diameters of the charges enhances the effect of reducing the amount of dust formation.

To confirm this effect during extraction of other rocks, we calculated the pressure depending on the spatial coordinate (Table 2) for basalt, diabase (Fig. 5), granite, gabbro, and limestone (Fig. 6). Such a calculation was conducted for the two cases: using the aqueous solution of iron (III) sulphate as the gap filler between the charge and the wall of a well, and when using water separately.

Table 2

Initial data to establish the dependence of pressure waves propagation on spatial coordinate for various types of rocks

Well diameter, mm	Charge diameter, mm	Rock characteristics			Characteristics of the gap filler between the charge and the wall of the well	
		Rock	Density, kg/m^3	Speed of sound, m/s	Density, kg/m^3	Speed of sound, m/s
250	160	Basalt	2,860	5,400	1,798	27,12
		Diabase	3,020	6,300		
		Gabbro	2,900	6,250		
		Granite	2,650	4,500		
		Limestone	2,550	4,550		
		Basalt	2,860	5,400	1,000	1,450
		Diabase	3,020	6,300		
		Gabbro	2,900	6,250		
		Granite	2,650	4,500		
		Limestone	2,550	4,550		

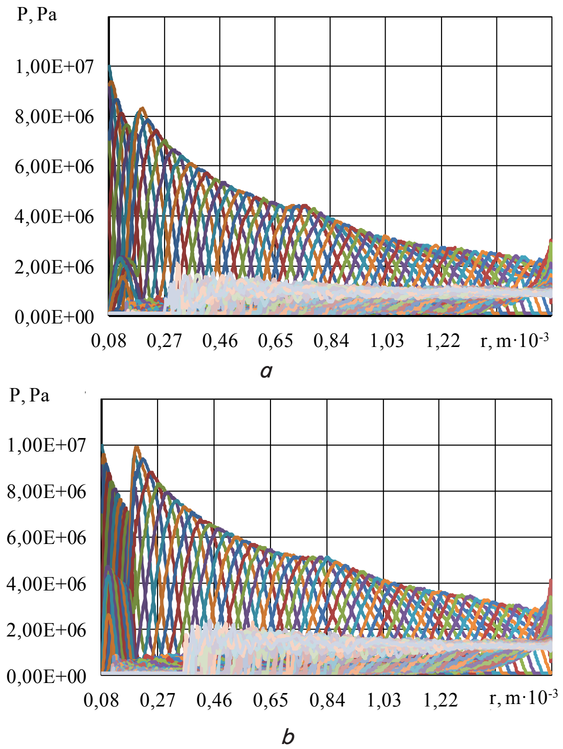

Fig. 6. Dependence of the pressure waves propagation on a change in the spatial coordinate when using as the gap between the charge and the well the aqueous solution of iron (III) sulphate (*a*) and water (*b*) while extracting limestone

The results of calculations show that the reduction of the pressure peak as a result of using as the gap filler the aqueous solution with a high acoustic rigidity is observed for all types of rocks. Particularly, this effect is best evident in the rocks with less acoustic rigidity (granite, limestone), and worse – in the rocks with larger acoustic rigidity (diabase), however it does not reduce its value (Fig. 5, 6). Thus, when blasting the limestones, the peak of pressure when using water as a gap filler between the charge and the walls of wells is 1×10^7 Pa. At the same time, when using the aqueous solution of iron (III) sulphate, it is about 8×10^6 Pa, which is 20 % less. The trend is similar for diabase; the difference between the maximum values of pressure in the zone close to the charge when applying water and the aqueous solution of iron (III) sulphate is about 15 %.

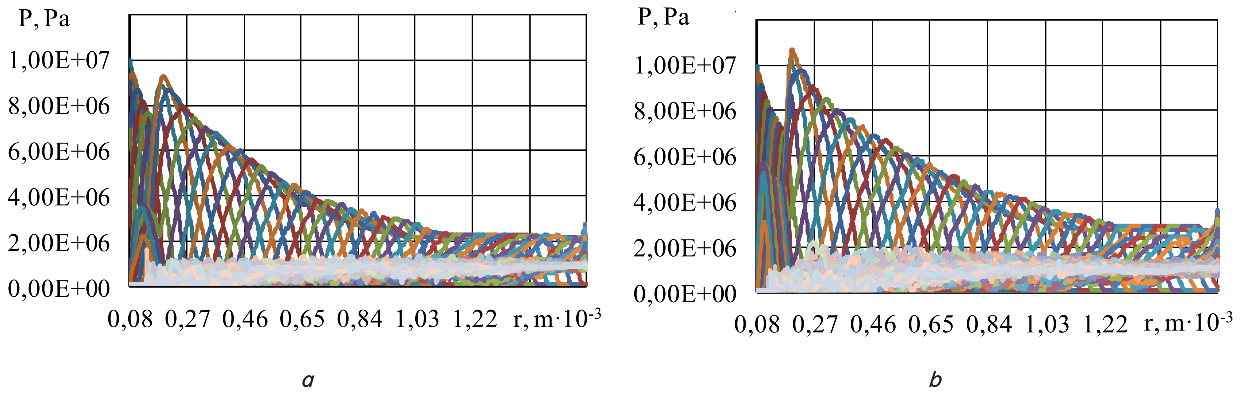

Fig. 5. Dependence of the pressure waves propagation on a change in the spatial coordinate when using as the gap between the charge and the well the aqueous solution of iron (III) sulphate (*a*) and water (*b*) while extracting diabase

6. Discussion of results of mathematical modelling of the process of explosive destruction of rocks

This research is aimed at improving the level of environmental safety during explosive destruction of rocks in quarries. That is implemented by improving the design of the charge using a radial gap between the charge and the wall of the well, which is filled with an inert substance that has high acoustic rigidity. There are studies [1–15], described above, that offer solutions to a given problem through technological, technical, and organizational measures. However, the common drawback is the impossibility to minimize dust emissions without reducing the effectiveness of rock destruction by explosion. It was not found how the design parameters of the charge could affect dimensions of the re-shredding zone without reducing the effectiveness of shredding. Still undetermined is the effect of the characteristics and properties of the gap filler between the charge and the wall of the well and its magnitude on the results of rock destruction by explosion.

The derived patterns in the propagation of pressure waves depending on acoustic rigidity of the gap filler between a charge and the wall of a well and its magnitude are based on the application of the McCormack finite-difference scheme of predictor-corrector [17, 18].

We confirmed influence of the magnitude of the gap between the charge and the wall of the well and its filler on the effectiveness of rock destruction by explosion and the amount of dust emission at a mass explosion.

The difference of this study from [1–15] is in that the process of explosive destruction of rocks is managed based on the adapted model by G.M. Lyakhov. Such a model, in addition to the characteristics of the rock and the explosive, makes it possible to take into account characteristics and the amount of gap filler between the charge and the wall of the well. Results of the calculation, based on it, show that an increase in the acoustic rigidity of the filler leads to a decrease in the peak of pressure in the zone close to the charge by 15–20 %. The increase in the magnitude of the gap through the application of charges with smaller diameters enhances the effect.

The benefits of this research include a possibility to use the developed approach for solving practical tasks. Particularly, in order to reduce the amount of dust formation during blasting operations. In addition, it is advisable to use it to improve quality of the blasted rocks (decreasing a resource loss by reducing the yield of re-shredded (sub-standard) fractions. It is known that the higher parameters of the detonation wave, the larger the stresses on the wall of the blast chamber and the larger the energy of dissipation, spent on re-shredding.

The shortcoming of the study conducted is a partial lack of experimental data. However, we are currently preparing an industrial experiment in order to measure the volume of dust emissions and to establish a fractional composition of the blasted rock. In line with the experiment design, there could be a research into the established theoretical dependences.

7. Conclusions

1. We have established the pattern in the propagation of pressure P waves related to the spatial coordinate r depending on acoustic rigidity of the gap filler between a charge and a wall of the well, its magnitude. It was determined that an increase in the acoustic rigidity of the filler reduces a peak of pressure in the zone close to charge by 15–20 %. The increase in the magnitude of the gap through the application of charges with smaller diameters enhances the effect of reducing the volume of dust formation.

2. We have established regularities in the propagation of pressure waves related to the spatial coordinate for various types of rocks. It was determined that the reduction in pressure peak as a result of using, as a gap filler, the aqueous solution with high acoustic rigidity is observed in all types of rocks. Particularly, this effect is best evident in the rocks with lower acoustic rigidity (granite, limestone), and worse – in the rocks with larger acoustic rigidity (diabase); it does not, however, reduce its value. When blasting the limestones, the peak of pressure when using water as a gap filler between the charge and the walls of a well is 1×10^7 Pa. At the same time, when using the aqueous solution of iron (III) sulphate, it is about 8×10^6 Pa, which is 20 % less.

3. It was found that solutions with larger acoustic rigidity will make it possible to decrease the amount of dust formation and increase the uniformity of fractional composition of the rock mass. That is implemented by a decrease in the amplitude of pressure waves at the media interface, by 20 % or more, and by an increase in the amplitude width by 25–30 %.

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