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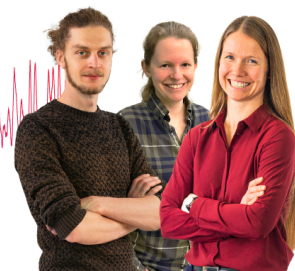
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# Numerical modelling of gas-dynamic processes and calculation results of gas-dynamic parameters in the charging chamber of a borehole

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**Abstract.** In this article, information on the numerical modelling of gas-dynamic processes and calculation results of gas-dynamic parameters in the charging chamber of a borehole is given. The article's main aim is to ensure the safety of the contour massif by optimizing the parameters of contour blasting based on the consideration of gas-dynamic processes during the excavation of deep horizons of underground mines.

## INTRODUCTION

The potential for integrating theoretical advancements in non-stationary gas-dynamic processes with the advent of cutting-edge computing and information processing technologies has driven the emergence of numerical modelling approaches to simulate rock destruction processes over the past decade. Accordingly, in the aforementioned work [1-9], the calculation model of the dynamics of rock destruction is preceded by the numerical modelling of the processes of formation and change of the stress state of the medium. In the aforementioned work, a one-step "large-particle" method for solving two-dimensional non-stationary problems of gas dynamics is presented. A study was conducted on gas-dynamic processes in a borehole and the loading of its walls during explosions of charges of various designs using a numerical solution of a two-dimensional non-stationary problem. In the solution, detonation and gas-dynamic processes, processes of product outflow through the mouth of the borehole, were considered, and based on the calculations, flow parameters were determined, including shock-wave, wave processes and dynamic loads on the borehole walls.

## EXPERIMENTAL RESEARCH

The energy release during the explosion of the charge was considered, taking into account the speed of detonation propagation along its length for various charge designs and initiation methods. For the sake of simplicity, the borehole walls were assumed to be rigid. Consequently, the detonation and gas-dynamic processes in the borehole can be described by the Euler system of equations, with the addition of a term to the energy equation describing the release of energy during detonation propagation. In integral form, the system of equations in a cylindrical coordinate system can be written for some arbitrary volume:

$$\left( \int_{\tau_L} \rho Z d\tau \right)_{t_2} - \left( \int_{\tau_L} \rho Z d\tau \right)_{t_1} = \int_1^2 \left[ \int_{S_L} C_n dS \right] dt + B \quad (1)$$

where  $Z$  and  $C_n$  are generalized hydrodynamic parameters that take the following values in pairs:

$$Z = \{1, U, V, E\}; \quad C_n = \{0, P^{(n-i)}, P^{(n-j)}, P^{(W-n)}\};$$

$$B = \{0, 0, 0, Q\};$$

$\tau_L$  - «Lagrangian volume»,  $S_L$  - is the surface of this volume,  $n$  - is the external normal to this surface,  $i, j$  - are the unit vectors of the coordinate system,  $W, U, V$  - are the velocity vector and its projections on the coordinate axes,  $E$  - is the total specific energy,  $P$  - is the pressure,  $\rho$  - is the density,  $t$  - is the time,  $Q$  - is the specific energy release.

For a cylindrical coordinate system  $r, z$ , with the  $z$ -axis coinciding with the borehole axis (well) and the origin at its mouth, we introduce a computational grid with cells  $\Delta r, \Delta z$  and the numbering of the sides shown in (Figure 1).

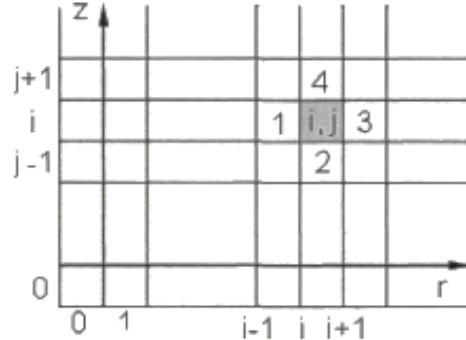


FIGURE 1. Coordinate system and computational grid.

Then, for some cell of the computational grid representing the «Euler volume»  $\tau E$  with the surface  $SE$ , the initial system of equations will take the form:

$$\left( \int_{\tau_L} \rho Z d\tau \right)_{t_2} - \left( \int_{\tau_L} \rho Z d\tau \right)_{t_1} = \int_{t_1}^{t_2} \left[ \int_{S_L} C_n dS \right] dt + \int_{t_1}^{t_2} \left[ \int_{S_L} \rho Z (W \cdot n) dS \right] dt + B \quad (2)$$

The system is supplemented by equations of the state of the medium. Since the air in the borehole, compared to the detonation products of the explosive, constitutes an insignificant part by mass, we will neglect its influence. Then the equation of state following the approach developed by the authors for constructing approximate equations of state [2] can be built in the form

$$P = \rho(k - 1)(e - B) \quad (3)$$

$$k = k_1; B = B_1 \text{ at } \rho < \rho_0; k = k_2; B = B_2$$

where:  $e = E - W^2/2$  is the specific internal energy,  $P$  is the pressure,  $\rho$  is the density,  $k$  is the adiabatic index, and  $W$  is the mass velocity with components  $u, v$  along the coordinate axes  $r, z$ .

The values  $\rho_0$  of  $k, B$  and - are functions of the density and composition of the explosive charge and are taken in accordance with the data of [1,2]. The values the coefficients included in equation for the explosives under consideration are given in Table 1.

TABLE 1. The values the coefficients included in equation for the explosives under consideration

EXPLOSIVE SUBSTANCE	$K_1$	$K_2$	$B_1, 10^{-6} \text{ J/kg}$	$B_2, 10^{-6} \text{ J/kg}$	$\rho \text{ kg/m}^3$
Granulite AC-8					
$\rho_0=1200 \text{ kg/m}^3$	1.6	1.2	0.055	0.424	4.47
$\rho_0=800 \text{ kg/m}^3$	1.6	1.2	0.099	0.424	2.38
Ammonite No. 6GV,					
$\rho_0=1100 \text{ kg/m}^3$	1.9	1.23	0.295	0.389	46.9
$\rho_0=800 \text{ kg/m}^3$	1.9	1.23	0.295	0.389	29.8

The system (1) ÷ (3) is closed by the boundary conditions:

- on the axis of symmetry  $U_{r=0} = 0$ ;
- on the borehole wall  $U_{r=r_{CKB}} = 0$ ;
- at the bottom of the borehole  $V_{z=H_{CKB}}$

At the mouth of the borehole, conditions are set for the free flow of gas in the case of a charge without tamping.

The non-stationary solution of the problem is represented as consisting of a sequence of time steps  $\Delta t$ , at each of which the system of equations (1) ÷ (3) is solved for each of the calculation cells, with boundary conditions (4). For

the numerical integration of the considered system of equations, a one-step difference scheme is used, constructed on the basis of the "large particle" method [3].

The adopted formulation of the problem allows us to estimate the relative changes in the gas-dynamic parameters during explosions of charges that are close to the energy release of explosives.

## RESEARCH RESULTS

The results obtained in [4,5] show that the difference in the pressure decrease on the pliable wall of the blast cavity, compared to the rigid one in a rock such as granite, is ~ 20%.

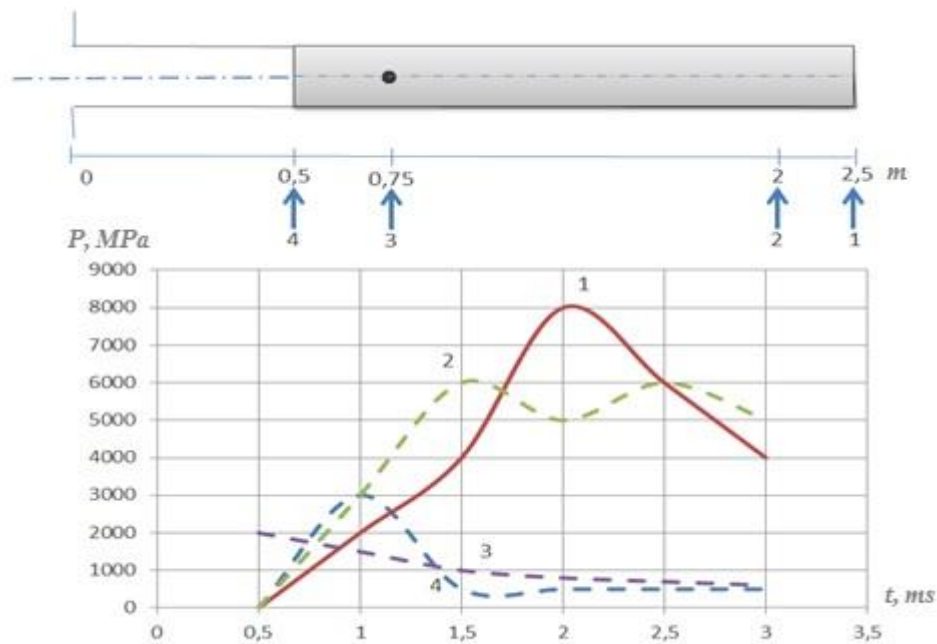
Based on the described numerical modelling technique, the parameters of the gas-dynamic processes were calculated, including the parameters of the dynamic loads on the borehole wall during explosions of charges of various designs and initiation options.

Figure 2 shows a diagram of the location of the calculation points for a solid charge design (point 2 corresponds to the location of the cartridge of the fighter), and also presents a calculated graph of the change in pressure on the borehole wall during blasting without tamping. Calculations were made for four points located along the charge axis. A solid charge of AS-8 granulite was loaded into a 2.5-meter-long borehole; the charge length was 2 meters.

The charge initiation was considered direct and reverse. It should be noted that reverse initiation is mainly used in mine workings.

As calculations show, at the moment of wave reflection from the borehole bottom during direct initiation, the pressure level in it quickly decreases to quasi-static in the bottom part of the borehole, and in the pre-mouth part, it remains somewhat lower than during reverse initiation. Subsequently, wave processes for both initiation schemes attenuate quite quickly.

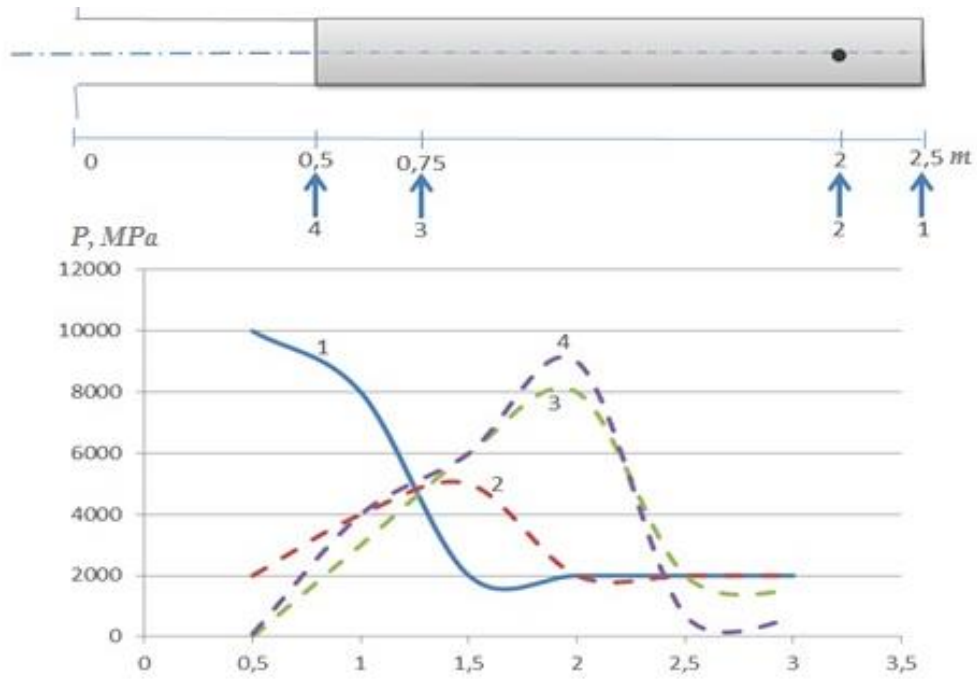
Violation of the one-dimensionality of wave propagation is observed only near the borehole mouth due to outflow, but this has virtually no effect on the flow inside the borehole.



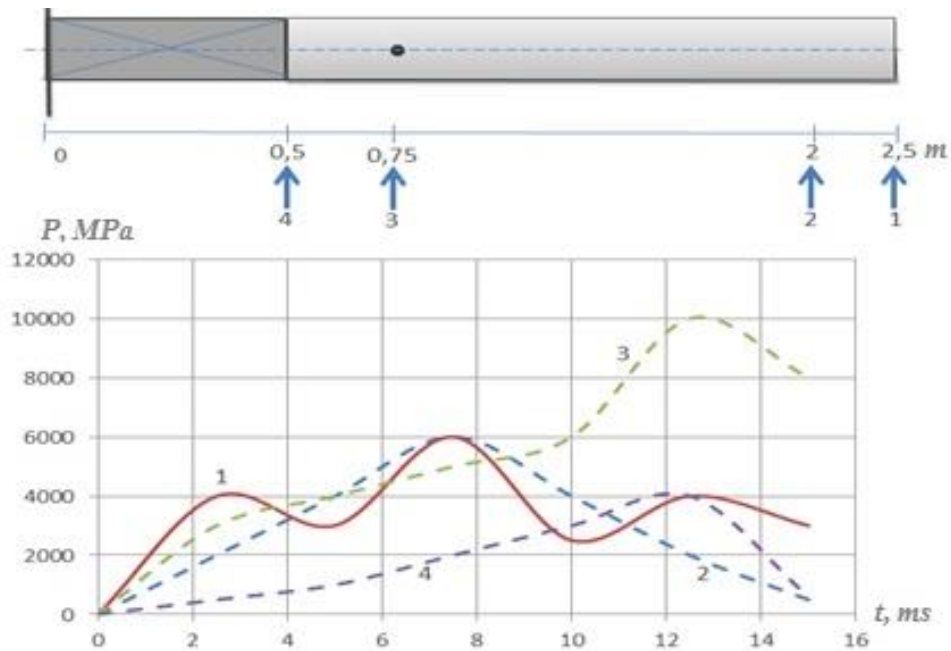
**FIGURE 2.** The design of a charge without tamping with a direct initiation method and the calculated graph of the change in pressure on the borehole wall during blasting without tamping with a direct initiation method: respectively along the length of the charge at points 1,2,3,4

With a decrease in the density of various explosives, the nature of the outflow is preserved with a general decrease in the pressure level. For granulite AC-8, when the density changes, all the main laws of the outflow are preserved, and the parameters at the front of the detonation and strong shock waves are higher, since the value of the adiabatic index is higher, but due to the lower heat of the explosion, the pressure decrease in the borehole and on its walls occurs

faster. Figures 3, 4 and 5 show the calculated charge designs with calculated points, as well as graphical dependencies of the change in pressure on the borehole wall over time.

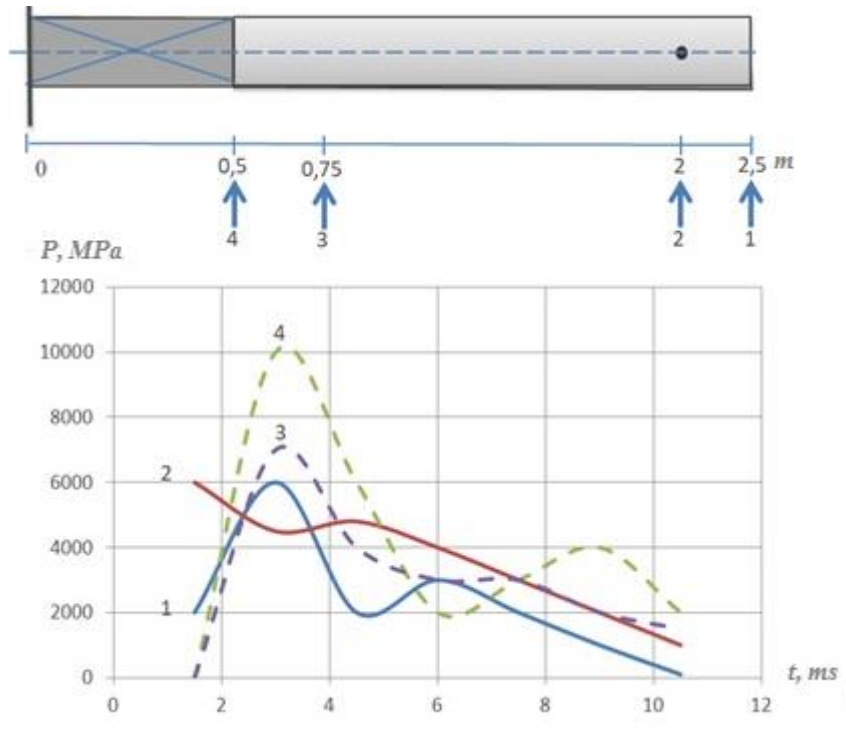


**FIGURE 3.** The design of a charge without tamping with the reverse initiation method and the calculated graph of the change in pressure on the borehole wall during blasting without tamping with the reverse initiation method: respectively along the length of the charge at points 1,2,3,4



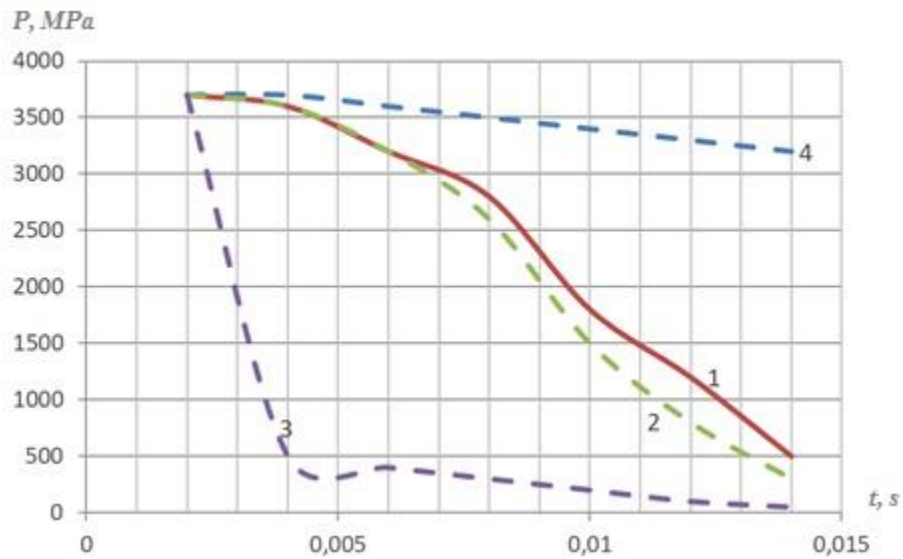
**FIGURE 4.** The design of a charge with a tamping with a direct initiation method and a graph of the change in pressure on the borehole wall during blasting using a tamping with a direct initiation method: respectively along the length of the charge at points 1,2,3,4

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**FIGURE 5.** The design of a charge with a tamping with a reverse initiation method and a graph of the change in pressure on the borehole wall during blasting using a tamping with a reverse initiation method: respectively along the length of the charge at points 1,2,3,4

The analysis of the results shows that in the presence of steaming in the borehole, the qualitative picture of the gas-dynamic processes changes. After the interaction of the detonation wave with the clay stemming, the parameters of the reflected shock wave propagating to the bottom of the borehole are comparable to the parameters of the detonation wave.



**FIGURE 6.** Graph of the total impact of the pressure of gaseous explosion products on the borehole wall depending on the charge design: 1 - charge with a profiled stemming; 2 - charge with a sand-clay stemming; 3 - charge without stemming; 4 - complete blocking of detonation products.

The pressure on the end of the stemming differs slightly from the pressure on the wall of the borehole near the stemming and decreases sharply at the exit as it is carried out. The shock wave experiences multiple reflections from the bottom of the borehole and the stemming, while the amplitude of the wave decreases quite slowly, and the quasi-static pressure level in the borehole increases somewhat. The dependence of the average pressure on the borehole wall on time (curve 1, Figure 6) shows that the pressure decreases when using sufficiently dense stemming is small, and only when the charge explodes without a stemming, an intensive drop in pressure is observed (curve 3). This is confirmed by the type of curves when using different stemming. The limiting case was the complete blocking of detonation products - a rigid wall instead of stemming. The difference between curve 4 corresponding to the limiting case and curves 1 and 2 in Figure 6 characterizes the decrease in pressure in the explosion cavity due to the outflow of detonation products through the borehole channel as the stemming is ejected. At the final stage, after the complete ejection of the stemming and part of the detonation products from the borehole, the intense wave processes in the explosion cavity fade.

It should also be noted that changing the charge length with a constant borehole diameter, or the detonation velocity with the ratio of the charge diameter to the borehole length remaining the same, only changes the time characteristics while maintaining all the qualitative features of the development of gas-dynamic processes.

Based on the calculations performed, the explosion impulse was determined for various charge designs.

In general, the explosion impulse  $I$  is a function of the pressure at the detonation wave front versus time  $P(t)$ , summed over the time of action  $\tau$  on the array of detonation products, i.e.

$$I = \int_0^{\tau} P(t) dt \quad (5)$$

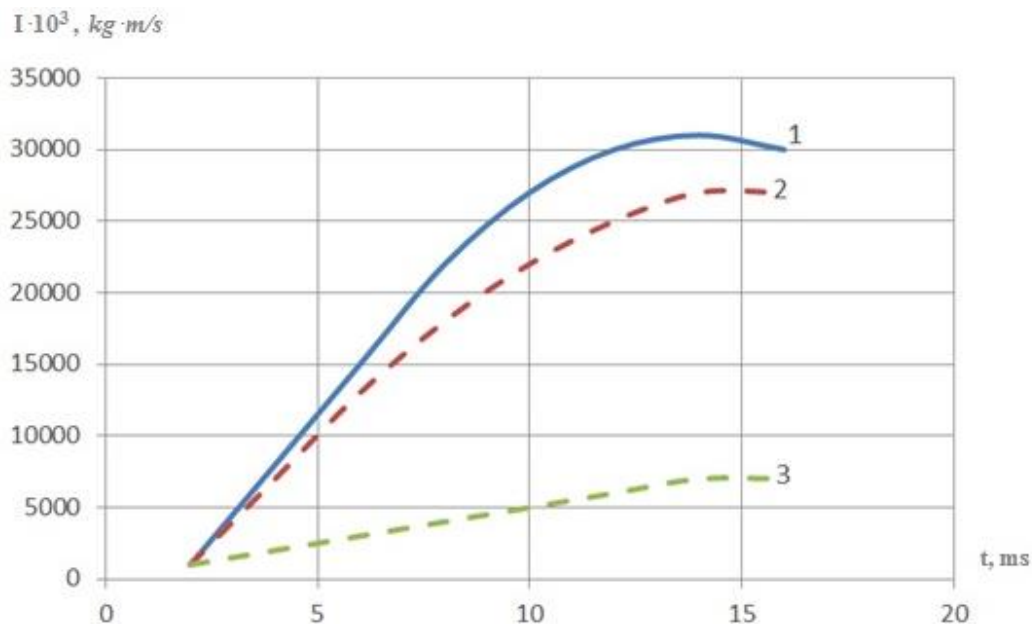
Based on the numerical results of the pressure in the charge cavity for various charge designs (Figure 6), the dependencies of the pressure change over time were obtained:

$$P(t) = -1,937 \cdot 10^7 t^2 + 4,284 \cdot 10^4 t + 3750 \quad (6)$$

$$P(t) = -6,7 \cdot 10^6 t^{1,75} \cdot e^{-5t} + 3750 \quad (7)$$

$$P(t) = 4,1 \cdot 10^3 e^{-500t} \quad (8)$$

Equation (6) describes the dependence for the charge design with a profiled stemming, (3), (8) - a charge with a sand-clay and without stemming, respectively. By integrating these dependences over time ( $\tau = 0 \div 15$  ms), it is possible to calculate the explosion impulses (Figure 7).



**FIGURE 7.** Graph of the dependence of the explosion impulse on time and the design of the charging device: 1 - charging device with a profiled stem; 2 - charging device with a sand-clay stem; 3 - charging device without the stem.

## CONCLUSIONS

The calculation results showed that the final time of the explosion pulse's active action for charges with profiled stemming is 13 ms, for sand-clay and without stemming—11 ms and 9 ms, respectively.

Thus, if we introduce the coefficient of the dynamic effect of the explosion pulse on the charge massif without stemming and take it as one, then this coefficient for charges with a profiled stemming and sand-clay stemming will be equal to - 1.44 and 1.22, respectively. The obtained coefficients of the action of the explosion pulse allow us to adjust the calculations of the specific consumption of charges of various designs.

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