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V. N. TYUPIN, *Professor, Doctor of Engineering Sciences, tyupinvn@mail.ru*
Belgorod State University, Belgorod, Russia

GEOMECHANICAL BEHAVIOR OF JOINTED ROCK MASS IN THE LARGE-SCALE BLAST IMPACT ZONE

The review of literature sources has allowed determining the mechanism of seismic blasts waves in jointed rock mass. The author presents the theoretical formulas for calculating stresses, relative strains and displacement velocities induced in rock mass by large-scale blasts. The formulas take into account the detonation characteristics of explosives, the borehole diameter, the length of explosive charges, the number of simultaneously blasted charges per groups and the factor of explosion energy redistribution to rock throw. Moreover, the formulas include the properties of rocks between the blasting point and a guarded object, and on the exposed surface of a guarded object. The compressive stresses, relative strains and displacement velocities in rocks are calculated from the formulas. The theoretically found change in the displacement velocity versus distance agrees with the field measurement data obtained in an open pit mine of Polyus company. The formulas of stresses and relative strains were used to define seismic impact exerted by large-scale blasts on the barrier of dry dock No. 1. Based on the calculated results, the recommendations are developed on reduction of seismic impact of blasts during dredging in the dock.

The research findings are applicable to developing blasting regulations toward reduction in seismic impact of large-scale explosions on exposed surfaces in rock mass, as well as on the ground surface structures and buildings.

Keywords: *seismic impact of blast, jointed rock mass, mechanism, stresses, strains, displacement velocity, numerical calculations.*
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Introduction

Blasting either in surface or underground mining exerts an adverse seismic impact on structures, buildings and exposed rock surfaces. The quantity of explosives is annually increased, which adds to the negative effect of seismic load of blasting on the surrounding mine structures and architectural objects.

In open pit mines, seismic blast waves affect open surfaces of highwalls and spoil banks, industrial and residential infrastructure both on ground surface and deep in rock mass. In case of underground mining, seismic impact of explosions induces rock falls and failure of pillars, deformation of roof support and initiation of rockburst-hazardous situations.

Many Russian and foreign scientists investigated the seismic load produced by blasting by theoretical analyses and during experimental observations [1–12].

In order to assess the geomechanical behavior of a jointed rock mass in the zone of seismic impact of blasts, it is necessary to define the mechanism of seismic blast waves.

M. A. Sadovsky thinks a rock mass is a complex hierarchy of blocks, and some blocks in this system, due to some causes (earthquakes, explosions), occur in the condition of energy exchange with the surrounding rock mass. The set of such blocks is named as “seismic focus” [1]. V. V. Adushkin points at the underground blast-induced formation of a cavity and damaged rock zones, i.e. inelastic deformation zones, which are the sources of seismic blast waves.

The mechanism and mathematical models developed in [13, 14] say that the stress wave in jointed rock mass crushes the joints intersected by an explosive charge, while quasistatic pressure of detonation products causes radial displacements of crushed and unbroken fragments in rock mass. As a result, the zones of crushed, block-fractured and fractured rocks appear. It is also supposed in [14] that seismic load of a blast is caused by high-velocity collision of crushed fragments in the crushing zone.

That is, the mechanism of seismic blast waves in jointed rock mass can be described as follows. An explosion creates a stress wave which crushes discontinuities intersected by an explosive charge. Then, the quasistatic pressure of detonation products induces radial displacement of crushed fragments and their high-velocity collision with surrounding rock mass. As a result, a seismic focus appears, and seismic blast waves from collision of broken fragments propagate from this focus. According to [15–17], the deformation zone in jointed rocks under large-scale blasting in open pit mines can reach 150 diameters of explosive charges starting from margin boreholes. In this case, collision of broken rock blocks and their crushing takes place at a distance to 20–30 diameters of explosive charges starting from margin boreholes. The most intense crushing of rocks occurs within 5 diameters of explosive charges, in the zone of smashing where stresses exceed the ultimate compressive strength of rocks.

The important geomechanical parameters of large-scale blasting are stresses, strains and PPV in rock mass. Knowing these parameters helps predict stability of exposed rock surfaces in open pit and underground mines. At present, the instrumental measurements allow determining the displacement velocities in rock mass and the permissible velocities for various surface and underground structures and buildings. The ultimate elastic strains for open surfaces of mine structures are given in [3, 10].

Sometimes, it is necessary to know stresses generated by seismic load of blasts if the strength parameters of rock blocks are known.

This study aims to find relations to determine stresses, strains and displacement velocities in jointed rock mass in the zone of seismic impact of a blast. The authors implement the numerical calculations and prove appropriateness of the formula of the displacement velocity in rock mass.

Relations for finding stresses, strains and displacement velocities

The mathematical model of stresses under explosion of a single explosive charge in a jointed rock mass is based on the law of energy conservation and is described in [15]. The same study presents the mathematical models with regard to interaction of a group of explosive charges during their simultaneous blasting in perpendicular and in parallel to the group; and with regard to interaction of a group of explosive charges during their short-delay blasting. The length of the charges and the index of redistribution of explosion energy to rock throw are also taken into account.

In a general form, the relation of the compression strength induced by a large-scale explosion nearby a guarded open surface (ground surface, exposed rock surface at the boundary of a mine structure or on a pit wall slope) has a form:

$$\sigma(R)=\frac{\sqrt{\pi}}{8}\frac{D\rho_C d_{ch} c_1 \nu_2}{R\Phi_1(1-\nu_2)}\left(1-\frac{\mu_1\nu_1}{1-\nu_1}\right)K_1K_2K_3K_4, \quad (1)$$

where D is the detonation velocity; ρ_C is the charge density; d_{ch} is the explosive charge diameter; c_1 is the P-wave velocity in the section between the blast and the guarded object; μ_1 is the friction coefficient between blocks in the explosion site; ν_1, ν_2 are Poisson's ratio of rocks in the explosion area and in the exposure areas, respectively; K_1 is the explosion potentiation in perpendicular or in parallel to the simultaneously blasted group of explosive charges; K_2-is the explosion potentiation in perpendicular or in parallel to planes of borehole rows behind the blasting perimeter during short-delay blasting; K_3 is the energy transfer factor from explosion to rock mass; K_4 is the explosion potentiation depending on the length of the charge; R is the spacing of margin boreholes in a block; Φ_1 is the average index of rock fracturing between a blasting point and a guarded structure.

The value of relative strains can be found from the formula [15]:

$$\varepsilon(R)=\frac{\sigma(R)}{E_2}\Phi_2=\frac{\sigma(R)}{\rho_2 c_2^2}\Phi_2, \quad (2)$$

where E_2, Φ_2 are the elasticity modulus and the index of rock fracturing in the region of a guarded structure, respectively; ρ_2, c_2 are the bulk density and P-wave velocity in rocks mass in the region of the guarded structure, respectively.

Placing of (1) in (2) allows the formula for evaluating relative strains in the region of a guarded structure:

$$\varepsilon(R)=\frac{\sqrt{\pi}}{8}\frac{D\rho_C d_{ch} c_1 \Phi_2 \nu_2}{R\Phi_1\rho_2 c_2^2(1-\nu_2)}\left(1-\frac{\mu_1\nu_1}{1-\nu_1}\right)K_1K_2K_3K_4. \quad (3)$$

Rock mass displacement velocity in the region of a guarded structure can be found from the formula [15]:

$$\upsilon(R)=\frac{\sigma(R)}{\rho_{rm}c_{rm}}=\frac{\sigma(R)}{\rho_2 c_2}\Phi_2^{0.5}, \quad (4)$$

where ρ_{rm} is the bulk density of rock mass ($\rho_{rm}\rho_2$); c_{rm} is the P-wave velocity in rock mass in the region of a guarded structure.

Placing of (1) in (4) produces

$$\upsilon(R)=\frac{\sqrt{\pi}}{8}\frac{D\rho_C d_{ch} c_1 \nu_2}{R\Phi_1\rho_{rm}c_{rm}(1-\nu_2)}\left(1-\frac{\mu_1\nu_1}{1-\nu_1}\right)K_1K_2K_3K_4, \quad (5)$$

or

$$\upsilon(R)=\frac{\sqrt{\pi}}{8}\frac{D\rho_C d_{ch} c_1 \Phi_2^{0.5}\nu_2}{R\Phi_1\rho_2 c_2(1-\nu_2)}\left(1-\frac{\mu_1\nu_1}{1-\nu_1}\right)K_1K_2K_3K_4. \quad (6)$$

The explosion potentiation factors in perpendicular to a longer side of a block (**Fig. 1**, marked with and arrow) are given by:

$$K_1=\ln 2{,}7[n-2\mu_1(n-1)];\ K_2=\ln 2{,}7[N-2\mu_1(N-1)];$$

$$K_3=\left(1-\sum_{i=1}^{z}\frac{a_i(n_i^*-1)}{2\pi W_i}\right)^{0.5};\ K_4=\ln 2{,}7\left[\frac{l_{ch}}{d_e}-2\mu_1\left(\frac{l_{ch}}{d_e}-1\right)\right], \quad (7)$$

where n is the number of boreholes in the simultaneous blasting group; N is the number of rows of boreholes; a_i is the distance between the boreholes in a row, or the half-distance between the borehole ends in fan blasting; n_i^* is the number of boreholes interacting in simultaneous blasting; W_i is the burden or the line of resistance at the bench bottom; z is the number of open surfaces nearby the blasted group of boreholes; l_{ch} is the length of explosion charge in a borehole; d_e is the block size in the blasted rock mass.

The analysis of relations (1), (3), (5), (6) and (7) shows that with increasing detonation velocity, charge density, charge diameter, number of boreholes in a group and number of groups of boreholes in short-delay blasting, charge lengths and the value of the burden, the values of stresses, relative strains and displacement velocities grow. This agrees with the studies in [1, 3, 4, 6, 7].

Furthermore, the analysis of relations (5) and (6) shows that in case of heavily damaged rock mass between a blasting block and a guarded structure (c_1 is minimal and Φ_1 is maximal), the displacement velocity is minimal. If the exposed surface is composed of heavily fractured rocks (ρ_{rm}, c_{rm} are minimal), the displacement velocity υ is maximal. The latter fact is experimentally proved in the field studies in open pit area of Zhelezny mine, Kovdor Mining and Processing Plant [5, 18]. The calculations from the relations presented in [5] show that at the same parameters (Q = 1000 kg, r = 200 m), the displacement velocity υ = 0.0071 m/s in IV–V category rocks, υ = 0.015 m/s in III–IV category rocks and υ = 0.03 m/s in II–III category rocks.

Let us calculate the displacement velocities υ versus the distance R from formula (5) and compare the results with the measurement data on seismic impact of large-scale blasts in an open pit mine of Polyus company [6]. The calculations were performed in perpendicular to the longer side of the blasting block (Fig. 1, marked with the arrow).

The calculation input data are: $D = 3.6\cdot10^3$ m/s; $\rho_C = 0.85\cdot10^3$ kg/m^3; d_{ch} = 0.25 m; $c_1 = 5\cdot10^3$ m/s; μ_1 =0.45; υ_1 = 0.25; Φ_1 = 9; υ_2 = 0.25; $\rho_{rm} = 2.7\cdot10^3$ kg/m^3; $c_{rm} = 3.5\cdot10^3$ m/s; n = 3; N = 10; l_{ch} =8 m; d_e = 0.5 m; K_1 = 1.18; K_2 = 1.63; K_3 = = 0.45 (three exposed surfaces are included: two slopes of a bench and one top site of a bench); K_4 = 1.9.

The calculation results on the displacement velocity from (5) are depicted by the curve in **Fig. 2**. The points demonstrate

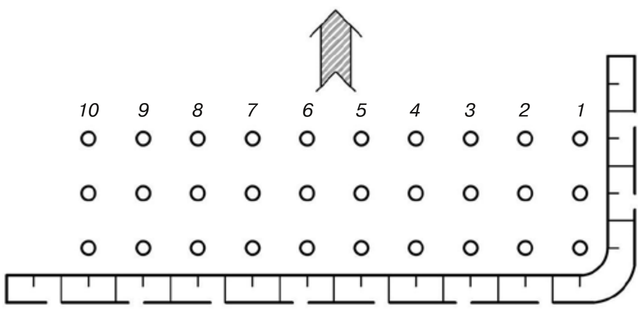

Fig. 1. Blasting pattern in bench:
1–10 — sequence of blasting of grouped boreholes (the arrow marks the direction of action of seismic blast waves)

Calculated stresses, relative strains and displacement velocities versus distance

Value	Distance from margin boreholes in blasting block, m					
	50	100	200	500	700	1000
σ(*R*), 10^5, Pa	8.68	4.34	2.17	0.87	0.62	0.43
ε(*R*)	0.00024	0.00012	0.00006	0.000024	0.000017	0.000012
υ(*R*), $\times 10^{-2}$, m/s	9.18	4.59	2.30	0.92	0.66	0.46

the experimental data from [6]. The comparison of theoretical data from (5) and field measurements taken in an open pit mine of Polyus shows good agreement of the results.

The numerical data on stresses, relative strains and displacement velocities found versus distance from formulas (1), (3) and (5) are compiled in the **table**.

The comparison of the relative strains in the table with the data from [3, 4] (allowable value of ε is 0.0001–0.0005) shows that blasting at the distance less than 150 m to "critical structures (waterworks tunnels, mine shafts, permanent galleries, crushing chambers, water drainages, shaft bottoms)" can induce irreversible straining in rocks.

Results and application

Relations (1) and (3) for determining stresses and relative strains were used with a view to reducing the seismic impact of blasting on the barrier of dry dock No. 1 during dredging. A critical structural element of sea–dock barrier is the clay-cement–concrete piles having ultimate compression strength $\sigma_c = 1.5 \cdot 10^6$ Pa and ultimate tension strength $\sigma_t = 10^5$ Pa. The value of the allowable relative strains is 0.0001. The piles are buried to a depth of 1 m in the parent granite–gneiss rock mass. Production blasting induced considerable displacements in the barrier and strains in the piles, which could result in bottom fracture of the piles.

The numerical calculations from formulas (1) and (3) show that, given the actual large-scale blast designs, blasting at the distance less than 100 m to the piles can induce stresses and strains higher than the permissible values. The developed recommendations on reduction of seismic impacts of blasts included: the increased delay interval; breaking toward the barrier; diagonal blasting patterns to decrease the burden and to ensure redistribution of blast energy for rock throw.

At the distance less than 150 m, it is required to reduce the number of boreholes involved in simultaneous blasting and the number of short-delay blasting groups of borehole. The application of the recommendation made it possible to reduce stresses and strain by a few times, and to ensure integrity of the piles.

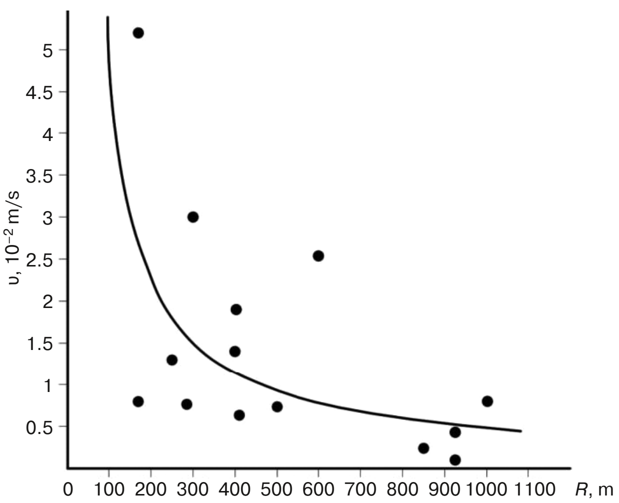

Fig. 2. Displacement velocity υ versus distance R. Points—field test data from [6]; curve—calculations from (5)

Conclusions

The review and analysis of literature, theoretical research and application of the research findings on a commercial scale has allowed drawing of some conclusions below.

1. The mechanism of seismic blast waves in the jointed rock mass is determined as follows. The blasting-induced stress wave disintegrates rock blocks intersected by an explosive charge. Then, the pressure of detonation products causes radial displacements of crushed fragments in the radial direction from the charge and induces high-velocity collision of the fragments and enclosing rock mass. This zone is assumed as the blast focus, and seismic blast waves propagate from it.

2. The theoretical formulas for calculating compressive stresses, relative strains and displacement velocity in rocks under large-scale blasting are presented. The formulas take into account the detonation characteristics of explosives, diameter of boreholes, length of explosive charges, number of of simultaneously blasted charges in a group, number of short-delay blasted groups of boreholes, and the factor of explosion energy redistribution to rock throw. The formulas also include properties of jointed rock mass between the blasting point and a guarded structure, and on exposed surface of a guarded object.

3. The numerical calculations of σ(*R*), ε(*R*), υ(*R*) from the formulas are presented. The displacement velocity calculations are compared with the actual data from an open pit mine of Polyus company.

4. The formulas of σ(*R*), ε(*R*) are used to determine stresses and relative strains induced by seismic impact of large-scale blasting on clay–cement–concrete piles and barrier in dry dock No. 1. Based on the calculation results, the recommendations on reduction in seismic impact of blasting during dredging are proposed.

5. The formulas of σ(*R*), ε(*R*), υ(*R*) are applicable to developing blasting regulations at the decreased seismic impact on exposed rock surfaces and surrounding structures and buildings.

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S. V. BARANOV [1], *Leading Researcher, Doctor of Physical and Mathematical Sciences, e-mail: bars.vl@gmail.com*
S. A. ZHUKOVA [2], *Senior Researcher, Candidate of Engineering Sciences*
P. A. KORCHAK [3], *Head of Rockburst Prediction and Prevention Service*
P. N. SHEBALIN [4], *Corresponding Member of the Russian Academy of Sciences, Doctor of Physical and Mathematical Sciences, Director*

[1] *Kola Branch, Geophysical Service of the Russian Academy of Sciences, Apatity, Russia*
[2] *Mining Institute, Kola Science Center, Russian Academy of Sciences, Apatity, Russia*
[3] *Apatit's Kirovsk Branch, Kirovsk, Russia*
[4] *Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Moscow, Russia*

SEISMIC PRODUCTIVITY OF BLASTS: A CASE-STUDY OF THE KHIBINY MASSIF

The authors study the property of production-scale blasts to induce seismic events classified as micro shocks, rock bursts and earthquakes caused by sudden slips along faults. The study area is the production performance zone of Apatit's Kirovsk Branch. It is situated in the southeast of the Khibiny Massif on the Kola Peninsula and is subjected to continuous autonomous seismicity monitoring. The subject of the research is the production blasts and seismic events recorded by the seismic monitoring station of Apatit's Kirovsk Branch between January 1996 and June 2019. Blasting-induced seismic events were identified using the nearest neighbor method and the seismicity-dependent proximity function of the space—time—magnitude (energy), calculated with respect to the blasts. The threshold of the proximity function to assume a seismic event as the blast-induced event was selected using the model-independent method of seismic catalog randomization. It is shown that the number of blasting-induced seismic events—blasting productivity—obeys an exponential distribution irrespective of magnitudes or occurrence depths of the studied events. The obtained result conforms with the earlier determined productivity law for natural earthquakes on a global and regional scale, as well as for mining-induced seismicity in the Khibiny Massif. Accordingly, the productivity distribution is governed by the properties of a medium and is independent of the source mechanism of a triggering event (explosion, seismicity).

Keywords: *production blasts, triggers, seismic events, productivity, exponential distribution, Khibiny Massif.*

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Introduction

Mining-induced seismicity in high-stress rock masses results in disastrous seismic events such as overlying rock collapse, rock bursts and manmade earthquakes. Such events are associated with great noise and various phenomena. Operating underground mines subjected to high confining pressure experience discontinuities in the adjacent rock mass in the form of spalling, extensile fracturing, micro shocks and rock bursts [1].

Blasting increases energy of seismic processes and, consequently, alters the seismic behavior in an area [2], particularly, in the areas of low seismicity. Regarding the East European Platform or Baltic Shield, for instance, the seismic energy of blasts exceeds the energy of tectonic earthquakes by a few orders of magnitude [3].