

RELIABILITY, STRENGTH, AND WEAR RESISTANCE
OF MACHINES AND STRUCTURES

Study of the Features of Crack Growth Rates
for Rocks upon Their Destruction
by the Explosive-Reactive Method

V. O. Solov'ev^{a,*} and I. M. Shvedov^{a,b}

^a Mechanical Engineering Research Institute of the Russian Academy of Sciences, Moscow, Russia

^b National University of Science and Technology MISiS, Moscow, Russia

*e-mail: solovievvo@yandex.ru

Received March 23, 2021; revised June 6, 2021; accepted June 24, 2021

Abstract—A model of gas-dynamic instability in an explosion channel using the explosive-reactive method for rock destruction is studied. The crack propagation rates and the regions of elastic vibration damping in a massif are determined. A critical amplitude threshold of elastic vibrations the exceedance of which indicates crack initiation in a continuous medium is proposed.

Keywords: rocks, explosive-reactive method, gas-dynamic process, crack growth

DOI: 10.3103/S1052618821050113

The results of simulation of nonstationary gas-dynamic processes during the operation of a portable explosive-reactive complex (ERC) are presented in [1]. The use of such complexes is quite relevant for solving a whole set of specific problems in the engineering-construction and mining industries. To increase the efficiency of using such complexes on soils with different physicommechanical properties, as well as on frozen and permafrost rocks, the features of development of the rock mass destruction process during the formation of a nonstationary gas-dynamic channel should be studied in more detail [2–4].

Previous studies established that the formation of a cavity in a rock by blasting is accompanied by the generation of an unsteady shock wave train, at whose fronts the pressure values are comparable to the pressure in the detonation product (DP) jet. The calculations performed in the axisymmetric problem statement showed that the rarefaction zones with a pressure lower than air pressure are formed at the same time. Such processes were simulated by the system of equations as follows:

$$\left\{ \begin{array}{l} \frac{\partial p}{\partial t} + v \frac{\partial p}{\partial x} + u \frac{\partial p}{\partial r} + \rho \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial r} \right) = -\frac{\rho u N}{r}, \\ \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0, \\ \frac{\partial u}{\partial t} + v \frac{\partial u}{\partial x} + u \frac{\partial u}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} = 0, \\ \frac{\partial k}{\partial t} + v \frac{\partial k}{\partial x} + u \frac{\partial k}{\partial r} = 0, \\ p = A \rho^k, \end{array} \right. \quad (1)$$

where p is the DP pressure, Pa; ρ is the DP density, kg/m³; r and x are the radial and axial distances from the channel center, m; v and u are the radial and axial mass velocities of DP, m/s; t is the time, s; k is the isentropic index; N is the number of medium particles in a unit mass (for cylindrical symmetry $N = 1$).

For setting the initial gas-dynamic conditions of the medium in the channel of the explosive-reactive block (ERB) of the ERC and in the cavity of the well formed, we used the parameters of the undisturbed standard atmosphere at $k = 1.4$. In the model calculations, the following experimental data were used for DP: $k = 3.05$; detonation velocity $D = 8730$ m/s; initial density of explosives $\rho_0 = 1780$ kg/m³. It was

assumed that the detonation of each explosive cartridge occurs instantaneously, and the parameters at the detonation wavefront are determined by the formula [5]

$$P_{in} = \frac{\rho_0 D^2}{k + 1},$$

where P_{in} is the DP pressure at the Chapman–Jouquet point, Pa.

System of Eqs. (1) was solved by the finite-difference predictor-corrector method of second-order accuracy in floating grids using the method of three-point smoothing [6].

The simulation showed that, during the interaction with the walls of the cavity being formed, a shock wave reflects repeatedly, and pressure pulsations occur in the working region. A similar process is observed in a supersonic flow jet in a damped cavity during the operation of the Hartman resonator.

The formation of resonance zones of pressure rise in the cavity being formed should also lead to non-uniform development of the process of the destruction of the surrounding rock mass due to the different rates of crack growth. It is hardly possible to verify this hypothesis experimentally.

In this work, we analyzed the rates of crack growth in a rock mass during ERB operation.

Due to evident challenges of studying the development of the entire gas dynamic process, in order to analyze and perform calculations, we selected a fragment of variation in the pressure values and Mach numbers from the simulation of the central channel during the ejection of sludge and the DP. It was earlier established that the motion dynamics of the expanding DP in the cavity being formed would in many respects be determined by the geometric configuration and gas-dynamic parameters of the DP [1]. In Figs. 1 and 2 the results of distribution of the gas dynamic parameters at ejection of products of rock fracture and gas in the vertical direction are shown with respect to the face area of the formed cavity [1].

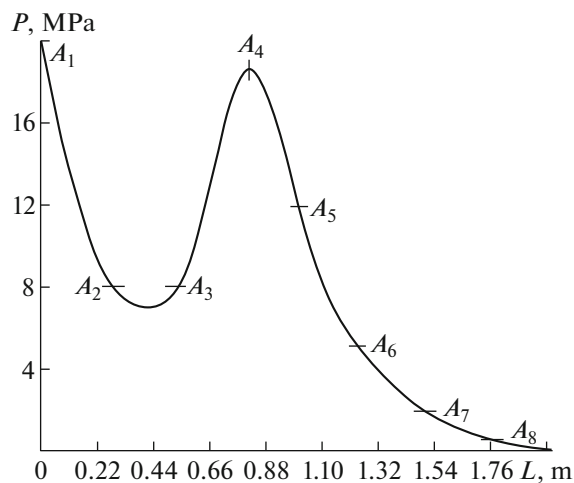


Fig. 1. Distribution of the pressure value in the central channel.

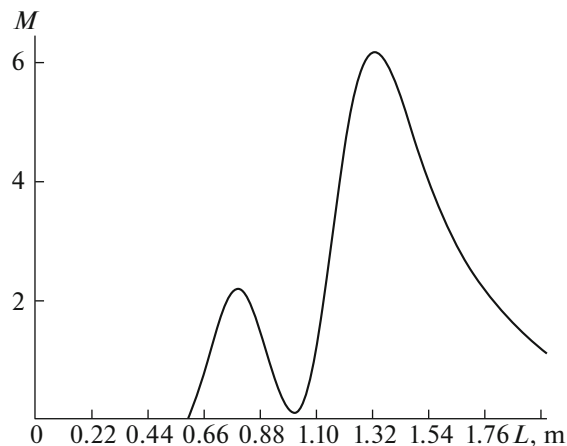


Fig. 2. Distribution of Mach numbers in the central channel.

We studied a generalized model of a massif as a continuous medium composed of rocks with medium strength without markedly expressed fracturing. We assumed that the physicochemical parameters of the massif, such as the volumetric density, elasticity modulus, Poisson ratio, and acoustic stiffness, are constant and typical of the whole study region of the development of the destruction process.

Quite a complicated process of blasting destruction in continuous medium models is the propagation of elastic compression waves at supersonic velocity. In the near zone, such a wave has a dynamic character with a steep leading edge and creates a complex stress state in the medium.

Simulating the development of the process of destruction of the rock mass usually involves the problem of explosive detonation in a blast hole, a well, or a pressure charge; i.e., the position of an explosive itself is statistically fixed and the problem is solved under conditions of cylindrical or spherical symmetry with the generation of a shock wave, its propagation deep into a massif at a supersonic velocity, and subsequent attenuation of the propagation velocity [7–9].

When the explosive-reactive block is in operation, the process of massif destruction becomes even more complicated due to dynamic deepening of the charge and the gas-dynamic instability being formed in the explosion channel. It is not easy to study such stochastic processes by mathematical simulation; this problem can be simplified by identifying boundary and initial conditions for a particular phase of vibrations.

To analyze the rates of crack growth in a rock mass for the phase of development of the gas-dynamic process under the operation of cartridges for deepening into a rock, we determined the crack growth rate as

$$v_{\text{cr}} = \frac{dr}{dt}, \quad (2)$$

where r is the distance from the central channel formed due to the ERB operation to the study region in the rock mass, m, and t is the time of onset of destruction of the study region after wave arrival, s.

Such time can be represented as the total arrival time t_1 of the compression wave and the time t_2 of the development of destructive shear stresses

$$t = \sum_{i=1}^2 t_i.$$

The simulation step was set with respect to the appearance of different zones of the shock wave. The near zone, the zone of appearance and propagation of a shock wave with a steep leading edge and a supersonic velocity, is usually detected within 3–7 radii of the explosive charge. The next zone is the zone of intense destruction, which is typical of compression waves, where the leading edge of the wave smoothens with the propagation velocities being similar to the sound velocities in a medium averaged over the physicochemical properties, not taking into account the heterogeneity of the rock mass. The further wave propagation has a seismic character with gradual damping. The compression wave arrival time t_1 can be determined by the formula

$$t_1 \approx \frac{r}{c_1},$$

where c_1 is the p -wave velocity in the rock mass

$$c_1 = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}. \quad (3)$$

For approximate estimations, we accepted $\nu = 0.25$ (Poisson ratio); for the elasticity modulus, we used its dynamic value E_d . Then, formula (3) takes on the form

$$c_1 \approx 1.1 \sqrt{\frac{E_d}{\rho}}. \quad (4)$$

The solution to the differential equation of form (2) with respect to time t_2 is presented in [10]

$$v_{\text{cr}} = \frac{c_1}{D_{\text{cr}}},$$

Table 1. Initial data for calculation

P_0 , MPa	20	8	8	17.5	12	5	2	0.5	0
L , m	0	0.25	0.5	0.75	1	1.25	1.5	1.75	2

where D_{cr} is the coefficient considering the crack growth rate with respect to the explosive parameters and the physico-mechanical properties of the rock mass. To solve the problem under conditions of cylindrical symmetry

$$D_{cr} = 1 + \frac{2(1 + \nu)\sigma_{tens}k_e}{\pi\rho_e e_e (k - 1)} r_{ar},$$

where σ_{tens} is the ultimate tensile strength of rock, Pa; k_e is the coefficient considering expansion of the DP of the linear-shaped charge to the lateral sides; e_e is the volumetric energy of the explosive, J/kg; k is the isentropic exponent; ρ_e is the density of the explosive, kg/m³; and r_{ar} is the relative distance to the point considered in a massif.

In the calculation, we considered the formation of the crack network in limestone with averaged parameters: $\sigma_{tens} = 10$ MPa; $k_e = 1.25$ (for medium-hard rocks); $e_e = 5700$ kJ/kg [11]. Substituting the values into formula (4), we obtain the coefficient D_{cr}

$$D_{cr} = 1 + 4.08 \times 10^{-4} r_{ar}. \quad (5)$$

In the calculations for finding the value of E_d , we used a correlation dependence between the static and dynamic elasticity moduli

$$E_{st} = 0.35E_d^{1.141}.$$

The mass velocity was determined as

$$v_m = \frac{P_0}{\rho D_1}, \quad (6)$$

where P_0 is the pressure in the shock wave, Pa, and D_1 is the velocity of the shock wave in the rock mass, m/s.

To analyze the crack growth rate, we considered a massif composed of sandstone with $\rho = 2700$ kg/m³ and the elasticity modulus $E_{st} = 65$ GPa. An elastic detonation wave propagates across the depth from the surface. We selected the points in the plot of pressure change (Fig. 1) and the data across the depth of the cavity being formed, which were used in the further calculations (Table 1).

With respect to the depth of the cavity being formed L , the expression for coefficient (5) has the form

$$D_{cr} = 1 + 4.98 \times 10^{-4} \times 12.5L.$$

Figures 3 and 4 present the calculation results as plots of change in gas-dynamic parameters of the blast wave and the rates of crack growth in the rock mass.

Figure 3 shows the plots of fluctuation of the crack growth rate in the rock mass with respect to gas dynamic instability at the developing front of the blast wave as the cavity deepens.

The rates of medium destruction grow at the segments of increasing pulsations of pressure. The estimated crack growth rates did not exceed the values of sound velocities in this medium. It is likely that it would be more correct to speak about the rate of development of some destroyed regions in the rock mass than about the crack growth rate itself, taking into account the acoustic properties of the medium.

With respect to the Mach number (Fig. 4), for the gas dynamic jet in the channel of ejection, the plot of change in the crack growth rates in the rock mass is more inertial. Supersonic pulsation of the flow velocities in a semiclosed space leads to resonance effects in the respective regions that are determined by the geometric parameters of the cavity and the parameters of detonation. The theoretical basis for the occurrence of such kinds of resonance effects was considered in detail in [12].

The amplitude of elastic displacement of particles in a rock mass was estimated at the different points of distribution of pressure values (Fig. 1) under shock wave propagation in the central channel.

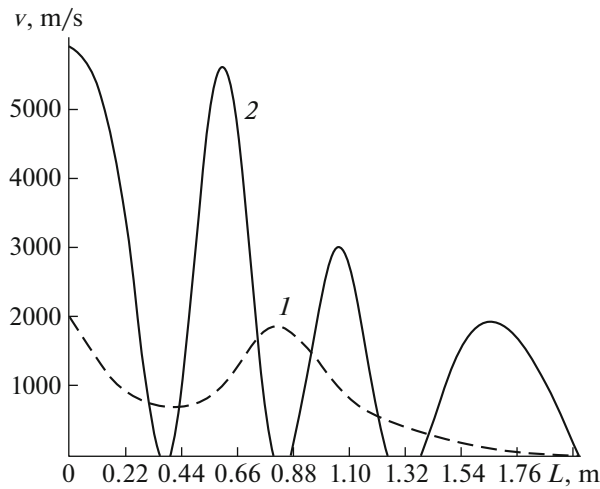


Fig. 3. Dynamics of crack growth rates with respect to pressure in a shock wave: (1) change in the DP pressure; (2) crack growth rate.

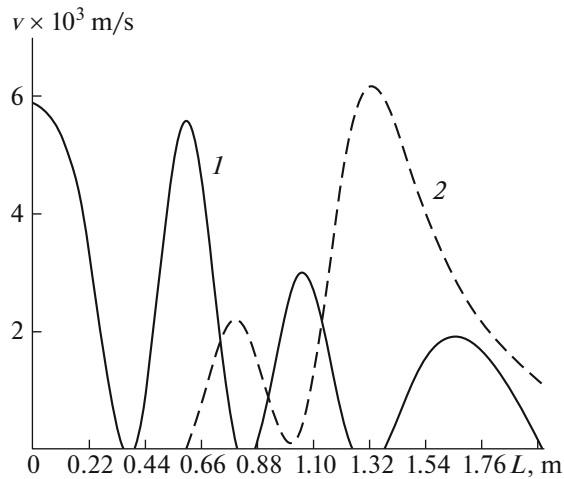


Fig. 4. Dynamics of crack growth due to pulsation of Mach numbers at the shock wave front: (1) crack growth rate; (2) Mach number.

From the condition that the initial velocity of the motion of rock particles at the interface with a gaseous cavity is obtained by formula (6) and is the maximum velocity at this time $v_{max} = A_0\omega$, where A_0 is the initial wave amplitude, nm; ω is the angular frequency, Hz, we have

$$A_0 = \frac{P_0}{2\pi f \rho D_{cr}}$$

where P_0 is the pressure at the point, Pa; f is the linear frequency, Hz; and ρ is the rock density, kg/m³.

Table 2 presents the values of initial amplitudes for the different points of a detonation wave.

Table 2. Initial data for calculating amplitudes of elastic wave damping for the different points of the detonation wave

P_0 , MPa	20	8	8	17.5	12	5	2	0.5
Study points	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
A_0 , nm	139	54	54	118	81	34	14	3

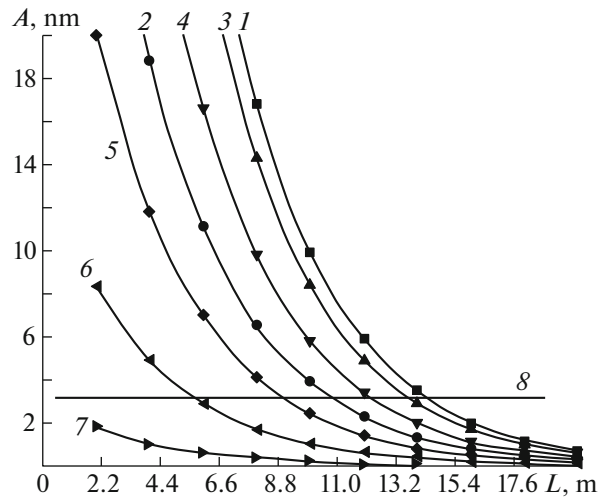


Fig. 5. Attenuation of the amplitudes of elastic vibrations for the unstable front of the shock wave in the rock mass: (1) A_1 ; (2) A_2, A_3 ; (3) A_4 ; (4) A_5 ; (5) A_6 ; (6) A_7 ; (7) A_8 ; and (8) level of critical amplitudes of the vibrations of elastic displacement.

The value of attenuating amplitudes was calculated by the formula

$$A = A_0 e^{-\theta r},$$

where θ is the absorption coefficient for the sandstone massif $\theta = 0.264, m^{-1}$, and r is the distance from the central channel to the point in the rock mass, m.

We calculated the amplitude of elastic particle displacement in the rock mass (at the different points of distribution of pressure values in a shock wave) during the shock wave propagation in the central channel.

Table 3 presents the calculation of the value of amplitude of elastic particle displacement in the rock mass with respect to distance r from the central channel of the ERB.

Using the data obtained, we constructed the graphs of the dependence of the amplitude values of decaying elastic oscillations in the rock mass on the distance to the central ERB channel for the points of shock wave at consideration (Fig. 5). In the study model of the rock mass, we used the hypothesis of a continuous medium regardless of the degree of its natural fracturing and heterogeneity. The goal was to perform a quality study of the concept of explosive energy conversion [13], in this case, into work of brittle failure according to Griffiths theory. The conditions for the creation of macroscopic discontinuities (cracks) and their further growth are related to accumulation and growth of dislocation defects of the crys-

Table 3. Results of calculating the amplitudes of elastic wave damping

Amplitude value, nm		Distance from the central channel to a point in the rock mass r , m									
A_0	A_i	2	4	6	8	10	12	14	16	18	20
139	A_1	81.2	48.4	28.5	16.8	9.9	5.9	3.5	2.0	1.2	0.7
54	A_2	31.8	18.8	11.1	6.5	3.9	2.3	1.3	0.8	0.5	0.3
54	A_3	31.8	18.8	11.1	6.5	3.9	2.3	1.3	0.8	0.5	0.3
118	A_4	69.6	41.0	24.2	14.3	8.4	4.9	2.9	1.7	1.0	0.6
81	A_5	47.7	28.2	16.6	9.8	5.8	3.4	2.0	1.1	0.7	0.4
34	A_6	20.1	11.8	7.0	4.1	2.4	1.4	0.8	0.5	0.3	0.2
14	A_7	8.3	4.9	2.9	1.7	1.0	0.6	0.4	0.2	0.1	0.071
3	A_8	1.8	1.0	0.6	0.4	0.2	0.1	0.075	0.044	0.026	0.015

tal structure. The analysis of the results of studying the features of crack growth in the different materials, including rocks [14–19], made it possible to identify the level of the lowest amplitudes of elastic vibrations the exceedance of which indicates crack initiation in the rock mass, in this case, the model rock mass, by assigning the value of interatomic planes for the crystal structures.

The performed calculation of the crack growth rates in the rock mass under the explosive-reactive method of destruction and the earlier simulation of gas–dynamic processes leads us to the following conclusions. (1) The estimated crack growth rates in the rock mass correlate with the sound velocities for the study rocks but do not exceed them in value. (2) The process of rock mass destruction refers to nonlinear processes corresponding to the resonance character of pressure pulsation in the gas–dynamic DP jet. (3) The growth of crack rates in the rock mass coincides with the growth of pressure in the shock wave, with the crack growth process dying at the peak of the wave pressure. (4) The fluctuation character of the change in amplitudes of the crack growth rates suggests the formation of regions with different intensities of destruction. (5) The critical amplitude threshold of elastic vibrations is proposed to be 3 nm, exceedance of which indicates crack initiation in the continuous medium. For the study model, during the operation of the ERC ERB, the maximum depth at which the local regions are destroyed in the massif is about 13 m. The most intensely destroyed region is found within a radius of 4–5 m from the central channel.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

1. Solov'ev, V.O. and Shvedov, I.M., Investigation of the gas–dynamic processes in the operation of an explosive-reactive complex, *J. Phys.: Conf. Ser.*, 2020, vol. 1451, p. 012018. <https://doi.org/10.1088/1742-6596/1451/1/012018>
2. Dugartsyrenov, A.V., Zarovnyaev, B.N., Shubin, G.V., and Nikolaev, S.P., Explosive destruction of complex structured frozen massifs with layers different in strength, *Vzryvnoe Delo*, 2017, no. 115–72, pp. 71–76.
3. Dugartsyrenov, A.V., Kim, I.T., Rakhmanov, R.A., Zarovnyaev, B.N., Shubin, G.V., and Nikolaev, S.P., Assessing the time of detonation products flow from a well dependent on parameters of charge cavity, *Vzryvnoe Delo*, 2015, no. 114–71, pp. 136–145.
4. Shevkun, E.B., Leshchinskii, A.V., Lysak, Yu.A., and Plotnikov, A.Yu., Long–period delay loosening blasting in open pit mines, *Gorn. Inf.-Anal. Byull.*, 2020, no. 10, pp. 29–41. <https://doi.org/10.25018/0236-1493-2020-10-0-29-41>
5. *Fizika vzryva* (Physics of Explosion), Stanyukovich, K.P., Ed., Moscow: Nauka, 1975.
6. Kestenboim, Kh.S., Roslyakov, G.S., and Chudov, L.A., *Tochechnyi vzryv. Metody rascheta* (Point Explosion: Calculation Techniques), Moscow: Mosk. Gos. Univ., 1974.
7. Torbica, S. and Lapcevic, V., Rock breakage by explosives, *Europ. Int. J. Sci. Technol.*, 2014, vol. 3, no. 3, p. 96–104.
8. Changyou, L., Jingxuan, Y., and Bin, Y., Rock-breaking mechanism and experimental analysis of confined blasting of borehole surrounding rock, *Int. J. Min. Sci. Technol.*, 2017, vol. 27, no. 5, pp. 795–801. doi <https://doi.org/10.1016/j.ijmst.2017.07.016>
9. Dugartsyrenov, A.V., On the fracture mechanism of elastic medium (rock) at explosion of a point and elongated charges, *Gorn. Inf.-Anal. Byull.*, 2008, no. 3, pp. 12–17.
10. Chernigovskii, A.A., *Primenenie napravlennogo vzryva v gornom dele i stroitel'stve* (Application of Directed Explosion in Mining And Building), Moscow: Nedra, 1976.
11. Kutuzov, B.N., *Metody vedeniya vzryvnykh rabot* (Methods of Explosive Works), Moscow: Gornaya Kniga, 2009.
12. Ganiev, O.R., Ganiev, R.F., and Ukrainskii, L.E., *Rezonansnaya makro- i mikromekhanika neftyanogo plasta. Intensifikatsiya dobychi nefii i povyshenie nefteotdachi. Nauka i praktika* (Resonance Macro- and Micromechanics of Oil Reservoir: Intensification of Oil Extraction and Enhancement of Oil Recovery: Science and Practice), Izhevsk: Inst. Comp'yut. Issled., 2014.
13. Solov'ev, V.O. and Shvedov, I.M., The concept of improving the efficiency of explosive energy converters, *J. Phys.: Conf. Ser.*, 2019, vol. 1172, p. 012007. <https://doi.org/10.1088/1742-6596/1172/1/012007>
14. Yang, X. and Wang, S., Meso-mechanism of damage and fracture on rock blasting, *Explos. Shock Waves*, 2000, vol. 20, no. 3, pp. 247–252.

15. Ko, T.Y. and Kemeny, J., Subcritical crack growth in rocks under shear loading, *J. Geophys. Res.: Solid Earth*, 2011, vol. 116, no. B1, p. B01407.
<https://doi.org/10.1029/2010JB000846>
16. Sivakumar, G. and Maij, V.B., Simulation of crack propagation in rocks by XFEM, *Proc. of the Conf. on Recent Advances in Rock Engineering (RARE 2016)*, 2016, pp. 291–296.
<https://doi.org/10.2991/rare-16.2016.46>
17. Ko, T.Y. and Lee, S.S., Characteristics of crack growth in rock-like materials under monotonic and cyclic loading conditions, *Appl. Sci.*, 2020, vol. 10, no. 2, p. 719.
<https://doi.org/10.3390/app10020719>
18. Yuan, H., Wang, F., Liu, Y., Bian, H., Chen, W., and Wang, Y., Time-dependent behavior of subcritical crack growth for rock plate: experimental and numerical study, *Int. J. Distrib. Sensor Networks*, 2018, vol. 14, no. 11.
<https://doi.org/10.1177/1550147718812019>
19. He, C. and Yang, J., Dynamic crack propagation of granite subjected to biaxial confining pressure and blast loading, *Lat. Am. J. Solids Struct.*, 2018, vol. 15, no. 6, p. e45.
<https://doi.org/10.1590/1679-78254463>

Translated by L. Mukhortova