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FEATURES OF FORMING AN EXPLOSIVE FRACTURE ZONE IN A HARD ROCK MASS

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The effect of extended discontinuities in a hard rock mass on regularities of forming explosive fracture zones is considered. The comparison of the numerical and in situ experimental results permits to conclude that, in common with the known effect of seismic blast wave screenage, transformation of the wavefront configuration is of drastic importance. In a number of cases, that results in the generation of complex-structured fracture zones: new fractured zones can form beyond unbroken areas. It is demonstrated that the similar effects may cause redistribution of the blast energy and, as a consequence, the higher seismic efficiency produced by flat charge blasting as compared with concentrated charge blasting.

Rock mass, blasting, fracture zone, seismic blast waves

INTRODUCTION

In spite of a variety of available publications, the studies into mechanical effect of underground blasting have not resulted in the complete understanding of deformation processes taking place in a rock mass under blast loads. Brittle-fractured hard rocks are of particular interest in this aspect. When describing mechanical and seismic blast effect on a rock mass, different methods of space averaging for properties of a medium and parameters of a mechanical motion have been used for many years. That provides efficient utilization of the developed apparatus of the continuum mechanics. A similar approach allowed the satisfactory precision to be reached in describing the basic aspects of the underground blasting effect, as calculation of a confined cavity volume, estimation of the intensive fracture zone and establishment of regularities in radiation and propagation of seismic waves [1]. It is essential to emphasize that the experimental data appeared far beyond the scattering boundaries for the employed average dependences. One of the reasons of this state of things is the discrete structure of a rock mass.

The widely known approach, based on the division of a medium into zones with different structural and mechanical characteristics, is convenient to analyze the mechanical state of a rock mass under the blast impact [1]. In many engineering applications, it is important to outline sections of different discontinuities under explosion action and to evaluate properly their specific sizes. The value of the maximum velocity of a medium displacement in a seismic wave with the known relative distance to the seat of explosion is considered the best to correlate average sizes of such zones [1].

This statement is true for many cases, but the analysis of experimental results obtained for a mechanical impact of underground blasts shows that the blasting effect in a rock mass is mainly determined by the medium structure [2, 3]. Even in the close vicinity from a charge, where stresses were considered to be so high that the medium behaves like a liquid in the first stage of the cavity expansion, the availability of discontinuities nearby the seat of explosion governs the asymmetry of the

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confined cavity [2]. As the distance from the seat of explosion increases, the mechanical effect of blasting depends to increasingly greater extent on the structural heterogeneities. Boundaries of rock fracture zones are often different tectonic disturbances: from faults to rather small fissures [2]. The fracture mode of a rock is mainly determined by existing mine workings, stress state of rock mass and its block structure [4 – 6].

Though well-known “screening action” of discontinuities consisting in reducing the seismic wave amplitude due to interaction with faults, fissures and erected structures [3], transformation of stress-strain state of a medium as a result of drastic change in the wavefront configuration has not been yet studied explicit. Alteration of the relationship between the stress tensor components may generate a number of important effects, some of them are considered in the present paper.

BLASTING IMPACT ON A ROCK MASS WITH STRUCTURAL DISTURBANCES

The analysis of observation data reveals that discontinuities in a rock mass can induce the formation of a fractured zone with a complex structure: beyond unbroken areas, new fractured zone can arise at large distances from a charge. In particular, this effect was observed when studying the blasting test site after experiments (explosion of hemispheric pressure charges 5 t in mass) carried out on the surface of a granite mass.

At the tested site in the hard rock mass is featured with complex structure. The engineering-geological exploration in the subsurface area of the rock mass revealed a few subhorizontal disturbances in the form increased fracturing zones with a width $h \sim 5 – 20$ cm. According to the test data, these subhorizontal disturbances substantially influenced the mode of the rock mass fracture under explosion. In Fig. 1 the scheme of the epicentral zone of the explosion is presented, plotted by geophysical exploration immediately after the explosion with a yield of 5 t.

The upper block of the rock mass in the epicentral zone of the explosion was practically fractured. The fracture zone did not imitate configuration of the explosion crater and extended further to periphery. The fracture zone formation stopped at interblock boundary I. In spite of essential amplitude of the impact (higher than 20 – 30 m/s), intensive formation of new fractures in rock block II was not observed. The elastic material characteristics of blocks II and III remained practically the same, but the local fracture zone of 20 – 30 cm was detected below the seat of the explosion in block II, at the depth of 4.5 m, and it did not expose a tendency to expand to periphery.

Numerical modeling data on the effect of blasting 5 t trotyl pressure charge in a hard rock mass, as applied to the test conditions were analyzed in order to study more profoundly the complicated mechanics of the fracture zone formation. We used 2D computer procedure [7] developed on the basis of Lagrangian numerical method “Tensor” [8].

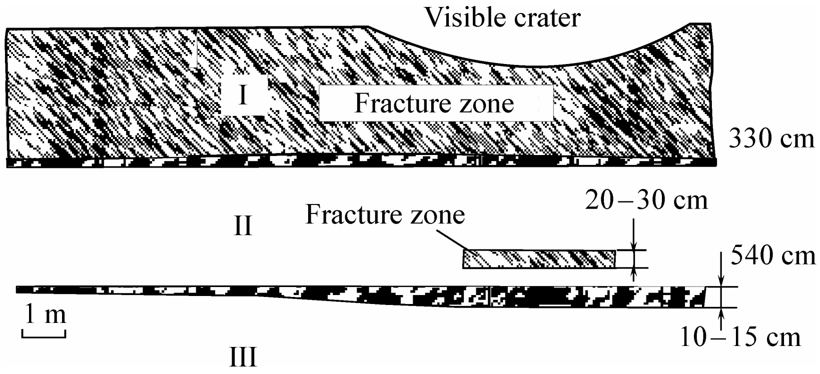

Fig. 1. Geophysical exploration in rock mass under the seat of explosion with a yield of 5 t

Describing the hard rock behavior involved an elastic-plastic model where the volume deformation law was expressed by the Murnaghan equation:

$$P = \frac{K_0}{n}\left[\left(\frac{\rho}{\rho_0}\right)^2 - 1\right], \tag{1}$$

where P is the pressure; K_0 is the modulus of dilation under zero pressure; ρ is the density; n is constant: $n = 3$ was assumed in the calculations. The generalized Mizes condition was used as a criterion:

$$J_2 = \frac{Y(P)}{3}, \tag{2}$$

where $J_2 = s_{ij}\, s_{ij}/2$ is the second invariant of the stress tensor deviator; s_{ij} are the components of the stress tensor deviator; Y is the shear strength. The function $Y(P)$ was taken as:

$$Y(P) = Y_0 + \mu P \Big/ \left(1 + \frac{\mu P}{Y_{PL} - Y_0}\right). \tag{3}$$

The hard rock was characterized by following constants: initial density $\rho_0 = 2670$ kg/m^3, longitudinal wave velocity $a_0 = 4500$ m/s, Poisson's ratio $\nu = 0.25$, $Y_0 = 100$ MPa, $Y_{PL} = 2$ GPa, $\mu = 2$. The problem was solved with consideration for weathered rock layer on the rock mass surface. When setting the model constants for weathering area, it was assumed that physico-mechanical characteristics of rocks vary linearly by depth, starting from $\rho_0 = 2620$ kg/m^3, $a_0 = 2570$ m/s, $\nu = 0.35$, $Y_0 = 10$ MPa, $Y_{PL} = 500$ MPa, $\mu = 0.6$ on the rock mass surface to the values cited for rocks in the main mass, in the vicinity of the weathering area. According to the research data, thickness of the weathering area was set as 1.5 m.

Higher fracture zones were modeled by soil interlayers with higher porosity and lower elastic and strength characteristics. Material of these zones was described by the elastic-plastic model of deformation of semi-rock soil [9]. Constants of the model were selected based on the engineering-geological research data obtained at the experimental site and based on the experimentally determined data on rigidity of simulated discontinuities. According to the data on structure of the site, three subhorizontal discontinuities were set to be at the depths $z = 3.1$ m, 5.4 m, 10.9 m with thicknesses of 20 cm, 10 cm, and 10 cm, respectively.

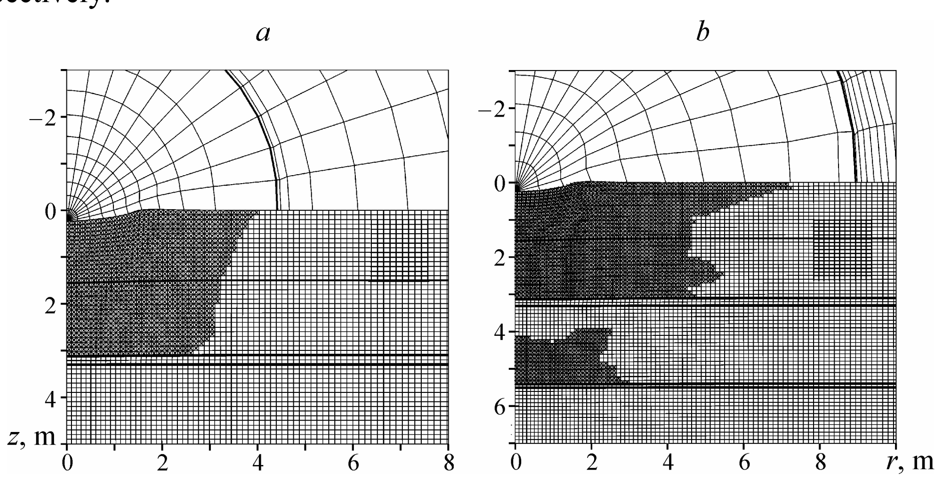

Fig. 2. Fragment of computational grid and the fracture zone configuration at time: a — $t = 1$ ms; b — $t = 3$ ms

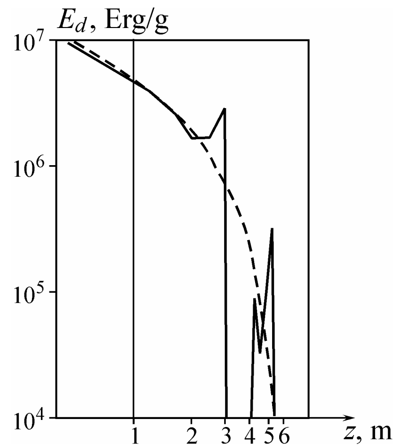

Fig. 3. Density of energy dissipated under rock fracture against depth (solid line — fractured rock mass, dashed line — homogeneous rock mass)

The calculated fracture zone configuration under explosion with a yield of 5 t is shown in Fig. 2. By the calculated data, subhorizontal discontinuity stops the fracture zone development at the depth $z = 3.1$ m. The rock fracture below the discontinuity (block II) starts at $z \sim 4.4$ м and expands downwards as far as the boundary of block III, and upwards. At being so, the upper boundary of the fracture zone stops at the depth $z \sim 4$ m, i.e., no rock fracture occurs directly under the first interblock boundary. Thus, according to the calculations, rock fracture does not occur in block II as deep as ~ 4 m, and then plastic process is observed down to the second discontinuity boundary. The post-test exploration of the rock mass showed that only local fracture zone at the depth of 4.5 m is observed below the seat of explosion in block II. This discrepancy is due to the fact that, in the used soil-deformation model, the term “fracture” refers to the alteration of rock properties within a rather wide range: from grinding to resuming of old fractures.

The degree of rock discontinuity after blasting in block II is much lower than in front of the first subhorizontal discontinuity, which is proved by the calculated dependence between the density of energy disseminated in mass as a result of a plastic process and the depth (Fig. 3). By the data reported in the present paper, the density of energy consumed for the rock fracture, in a narrow zone exclusively, in the close vicinity to the second subhorizontal fracture, is nearly 1/5 of the minimal density of energy dissipated above the first fracture, and this difference reaches $20-40$ times as the distance from the second fracture increases.

When analyzing the calculated and experimental data, our attention was attracted to the fact that the rock fracture beyond the structural discontinuity can take place at essentially lower parameters of the mass velocity in a seismic zone as compared to an explosion in a homogeneous rock mass. The results reveal that, in addition to the screening action of a fault or a fissure, the rock mass fracture process is greatly influenced by variations in geometric characteristics of the seismic wavefront due to the interaction with the discontinuity. Geometric variations of the wavefront are conditioned by the change in ratio of the stress tensor components, and the latter influences directly has the process of the shear fracture in the hard rocks. Figure 4 illustrates the above statement by presenting the diagrams of movement velocities, normal components of stress tensor and the square root of the second invariant of the stress tensor deviator, characterizing the shear load level, as it is known, the value of the above square root determines the intensity of the shear stresses. We see that it is possible to gain markedly higher shear loads at the same amplitude of the spherical wave velocity.

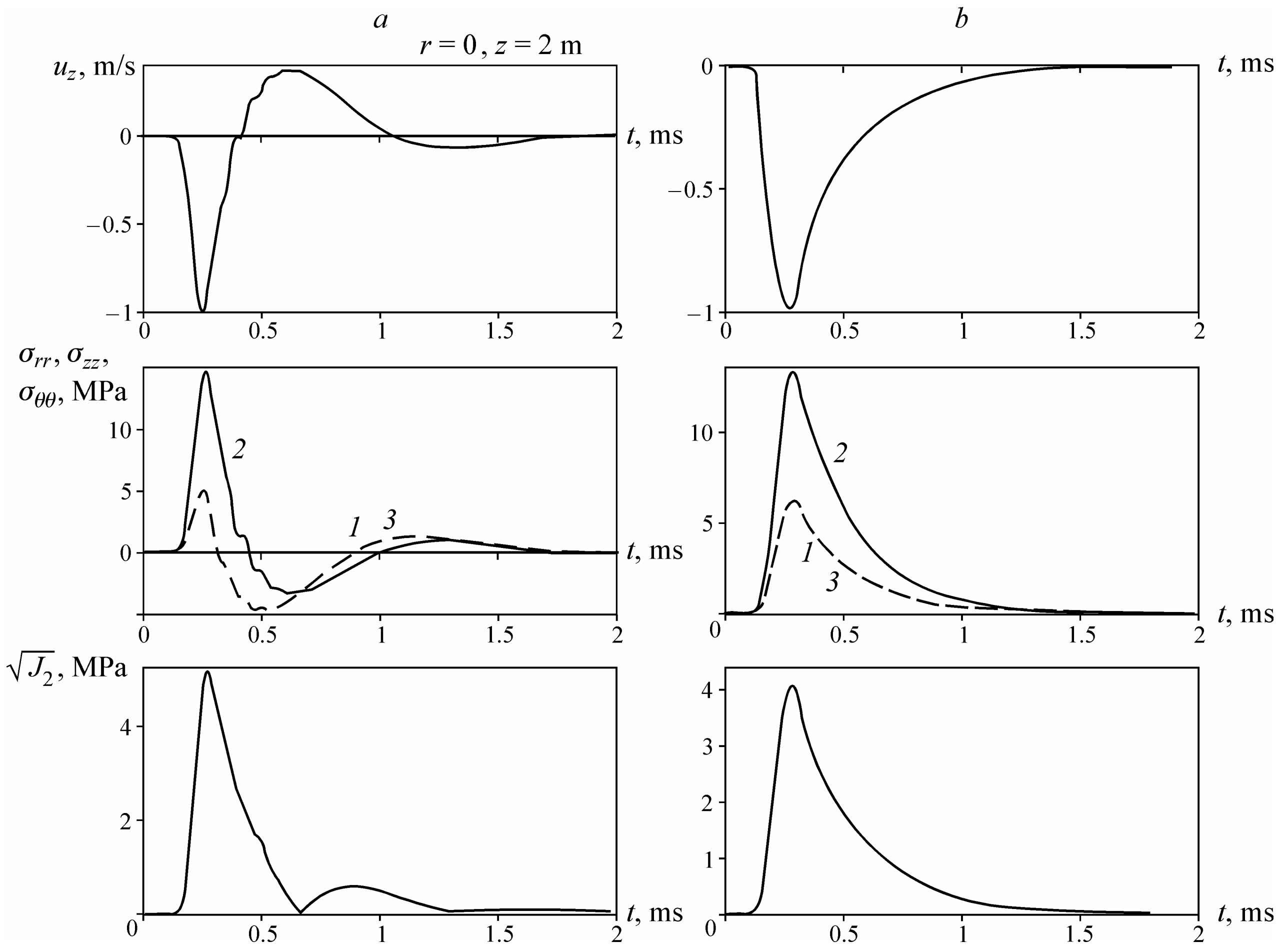

Fig. 4. Diagrams of velocity, normal components of stress tensor (*1* — σ_{rr}, *2* — σ_{zz}, *3* — $\sigma_{\theta\theta}$) and square root of the second invariant of stress tensor deviator for (*a*) spherical and (*b*) plane waves

Thus, in the case of a subhorizontal discontinuity with a low shear strength, the refracted wave below the seat of explosion is close to a plane wave, and, consequently, the fracture within it occurs under higher velocity amplitude. As the distance from the fracture increases, the seismic wave, again, transforms into a quasi-static wave for which the shear stresses are proportional w_R / R, where w_R are the radial shears; R is the distance to the spherical wave source. In the zone of the lower fracture edge, R may be rather small, thus, giving rise to rather high shear stresses, resulting in rock fracture under lower maximum velocity as compared to a homogeneous rock mass.

Consider in more detail the peculiarities of the fracture zone formation in a rock mass with geostructural disturbances on the basis of the calculation data on blasting hemispheric pressure charge with 1 t explosive on the surface of the rock mass with a single horizontal fracture zone 10 cm in width at the depth of 2.5 m. In the calculations, the following rock mass characteristics were assumed: density $\rho_0 = 2760$ kg/m^3, longitudinal wave velocity $a_0 = 5500$ m/s, Poisson's ratio $\nu = 0.25$, strength under zero pressure $Y_0 = 100$ MPa, limit strength $Y_{PL} = 2$ GPa, $\mu = 0.9$. The rock characteristics in fracture zone were varied in order to provide the wide-range variation in coefficient A of the wave attenuation by a disturbance (ratio of the shear velocity amplitudes in the incident u_2^m and a passed u_1^m waves $A = u_2^m / u_1^m$). The calculation results reveal a tendency of change in the rock mass fracture mode below the fracture zone under variable screenage properties of the disturbance. When fracture screening of the wave is weak (A is close to 1), the hard rock fracture below the fracture proceeds similar to that in the homogeneous rock mass. As screening increases, the extension of the fracture zone below the fracture reduces first of all in horizontal direction, and an area of destroyed rock is separating from the fracture. Moreover, the rock fracture below the fracture starts nearby the upper edge of the forming fracture zone and expands downwards (in rock mass). By the calculated data, we determined the wave attenuation coefficients at which the fracture zone starts separating from the lower surface of the disturbance ($A_m \approx 0.56$), and the rock fracture practically stops below the fracture zone ($A_{\min} \approx 0.33$). In Fig. 5 the rock fracture zone configuration is shown for the determined values of the wave attenuation coefficients.

The data obtained allow establishing a relationship between the presence of the rock fracture zone below a fracture and the velocity amplitude for a seismic wave passed through the fracture, and comparing this value with the velocity amplitude in a seismic wave which induced the rock fracture in a homogeneous rock mass. Thus, in Fig. 6 the depth-dependence is given for the maxima of the rock movement velocity and the stress tensor component σ_{zz} below the seat of explosion, that were obtained for three calculation variants: blasting in a homogeneous rock and blasting in rock masses with fracture zones at attenuations A_m and $A_{\min}$.

In calculations of a blasting effect in a homogeneous rock mass, the fracture zone size below the explosion epicentre was ~ 4 m. In the curve $|u_z^m|$ (Fig. 6), the arrows denote the points corresponding to location of the fracture zone boundaries in the calculations of homogeneous rock mass blasting and to locations of the upper and lower fracture zone boundaries in the calculations of fractured rock mass blasting. The obtained diagrams show that in the close vicinity from the lower boundary of the fracture zone, fracture does not occur if the parameters of seismic explosive waves are much higher than those at the fracture zone boundary in the homogeneous rock mass. Thus, in the homogeneous rock mass, the maximum rock movement velocity in the seismic wave corresponds to the fracture zone boundary and amounts to approximately 15 m/s; in the case of the fracture zone calculations, there is no fracture nearby its lower boundary, where the velocity reaches 22 m/s (variant $A = A_m$). However, at the points spaced by 1 m from the fracture zone, fracture takes place at substantially lower amplitudes of the seismic-blast waves as compared to the homogeneous rock mass. Thus, the local rock fracture in the calculated variant at $A = A_{\min}$ is observed at $u_z^m \approx 8$ m/s.

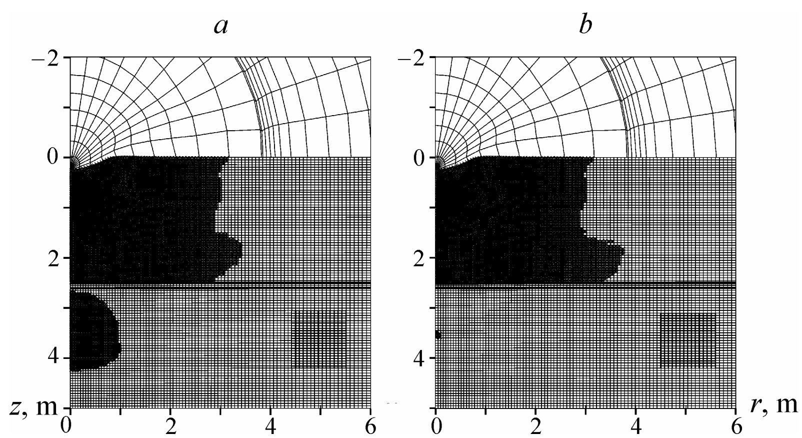

Fig. 5. Fragments of computational grid and the fracture zone contours at $t = 1$ ms and (a) $A = A_m$ and (b) $A = A_{\min}$

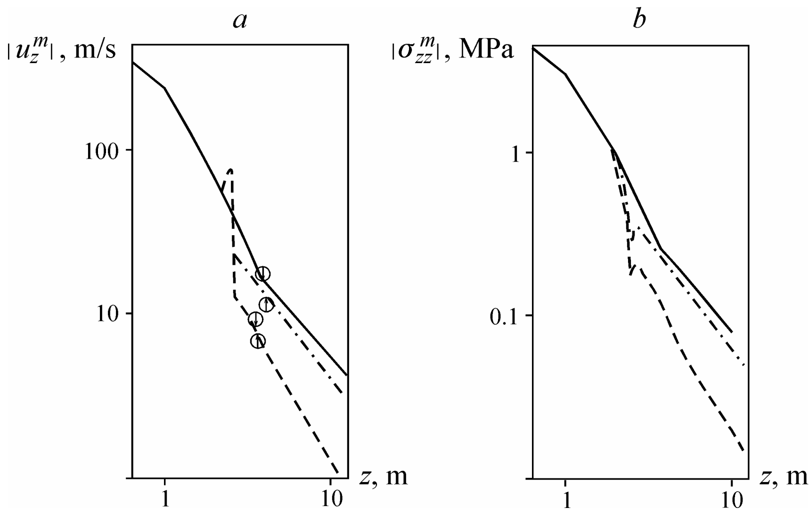

Fig. 6. Depth distribution below the seat of explosion epicentre for (a) maxima of velocity and (b) stress tensor component σ_{zz} in rock mass with fracture (dash-dot lines — A_m; dash lines — $A_{\min}$) and in homogeneous rock mass (solid lines)

The reported data show explicitly that the correlation, specific for a homogeneous rock mass, between the characteristics of stress-strain state of rocks and the amplitude of the medium movement velocity can be broken under the seismic effect in a block rock mass. The similar effect may be gained artificially by blasting a concentrated extended charge as a seismic source.

DECKED CHARGE BLASTING

The seismic wave produced by blasting a plane decked charge at distances, equal to an order of lateral size of the charge, has close-to-plane front. Therefore, if the extension of this charge exceeds the size of the fracture zone after the concentrated charge blasting with the same yield, we may expect that the charge shape would produce visible effect on the fracture zone configuration in blasted hard rocks and, respectively, on the seismic effect parameters under remote blasting. Let us exemplify that by a numerical solution of the problem on blasting an explosive that fills a plane extended fracture in a hard rock mass. As per 2D numerical procedure used, the calculations were performed in the axis-symmetrical problem setting, namely, in the calculations, the fracture shape was assumed as disc. The axis z of the cylindrical coordinate system is the symmetry axis of the disc-shaped charge, and the axis r is located in the plane of the charge symmetry. Rock deformation was described by the generalized quasi-elastic-plastic model [9]. The basic rock characteristics were preset as follows: density $\rho_0 = 2800$ kg/m^3, longitudinal wave velocity $a_0 = 3000$ m/s, lateral wave velocity $b_0 = 1440$ m/s. Explosion of a trotyl charge was considered in a fracture with thickness $h = 2$ cm and radius $R_j = 10$ m. As it was mentioned above, the expected effect at the fixed ratio h / R_j should be greater under reduced total yield of explosion, in the calculations the average density of the trotyl charge was preset $\rho_{tnt} = 160$ kg/m^3. Such low density of charging is possible by employing, for example, a charge with air gaps or an explosive with an inert filling material. Trotyl mass in the fracture was ~ 1000 kg. The charge detonation is initiated from the axis z.

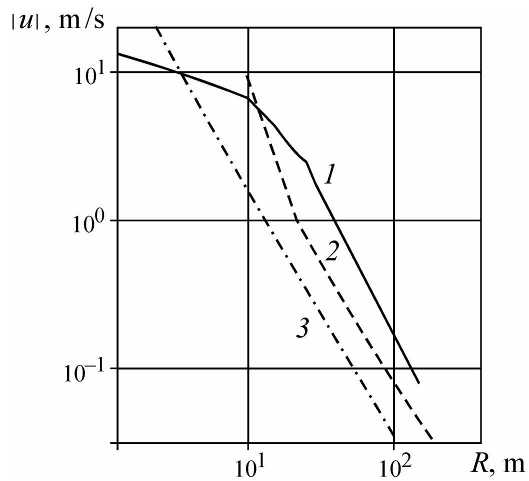

Fig. 7. Dependence of maximum soil movement velocity on distance: *1* — in perpendicular to the plane of the disk charge; *2* — along the direction lying in the plane of the charge ($z = 0$); *3* — confined explosion of spherical charge

In Fig. 7 the spatial distribution of the maximal rock movement velocity, obtained in the calculations of the disk charge blasting, is compared to the calculated data on the confined explosion of a spherical charge with the same yield and average density. According to the calculation results, at distances more than the fracture radius, the amplitude of the soil movement velocity under flat charge blasting appreciably exceeds the analogous parameters of the seismic wave generated by the concentrated charge blasting, even in the direction of the fracture end-face. At a first glance, this result contradicts to a simple conclusion based on the energy conservation law, according to which the confined blasting of charges having the same yield but different shapes, at rather large distances should initiate seismic waves of approximately equal intensity. However, consider in detail the energy balance of blasting in a thin extended fracture and compare it with the energy balance of the confined blasting of a spherical charge. In Fig. 8 the time-dependences are presented for the share of the internal and kinetic energies in plastic deformation zones and beyond fracture zone, obtained in the calculations of the confined blasting of a spherical charge and blasting in fractures 2 cm in thickness, with 1 m and 10 m radii. In the view of the simplification, the calculations were performed by approximation of instant detonation of explosive. The data in Fig. 8 are normalized with regard to the full blast energy. It is important that the internal energy in the rock fracture zone includes both the accumulated deformation energy and the energy dissipated during plastic transformation, and presents the common potential energy beyond the fracture zone. The data from Fig. 8 are summarized in Table 1.

By the calculated data, the complete energy transferred to a rock mass by blasting differs negligibly in all the cases, and amounts to 37 % of the total blast energy for a spherical charge and approximately 50 % for blasting in the fracture with radius of 10 m. However this energy is expended in rock mass in different ways. Under the spherical charge blasting, the basic energy is consumed to fail rocks. Under blasting in a fracture, the seismic wave is radiated and its front shape is close to plane in the vicinity to the source. Correspondingly, decked charge blasting in a fracture in order to fail rocks provides substantial reduction in the energy losses. And as the area size, where the generated seismic wave is close to a plane one, tends to increase as the fracture extension grows, the losses of the dissipated energy should be less for the fractures with larger radii. The data in Table 1 are in compliance with this conclusion. According to the calculation results, the share of seismic waves radiated outside the fracture zone amounts to approximately 8 % of the spherical charge blast energy and to about 27 and 39 % of blasting in fractures with radii of 1 and 10 m. Thus, by the seismic effect at large distances, the blasting in a fracture with 1 m radius (explosive mass is 0.01 t) should correspond to blasting a spherical charge about 0.03 t in mass, and explosion of 1 t explosive in a fracture of 10 m radius — to blasting a spherical charge about 5 t in mass. The derived conclusion is confirmed by the comparison of spatial distributions of maximal soil movement velocities under blasting in fractures with radii of 1 and 10 m and explosions of spherical charges of 0.03 and 5 t, respectively (Fig. 9).

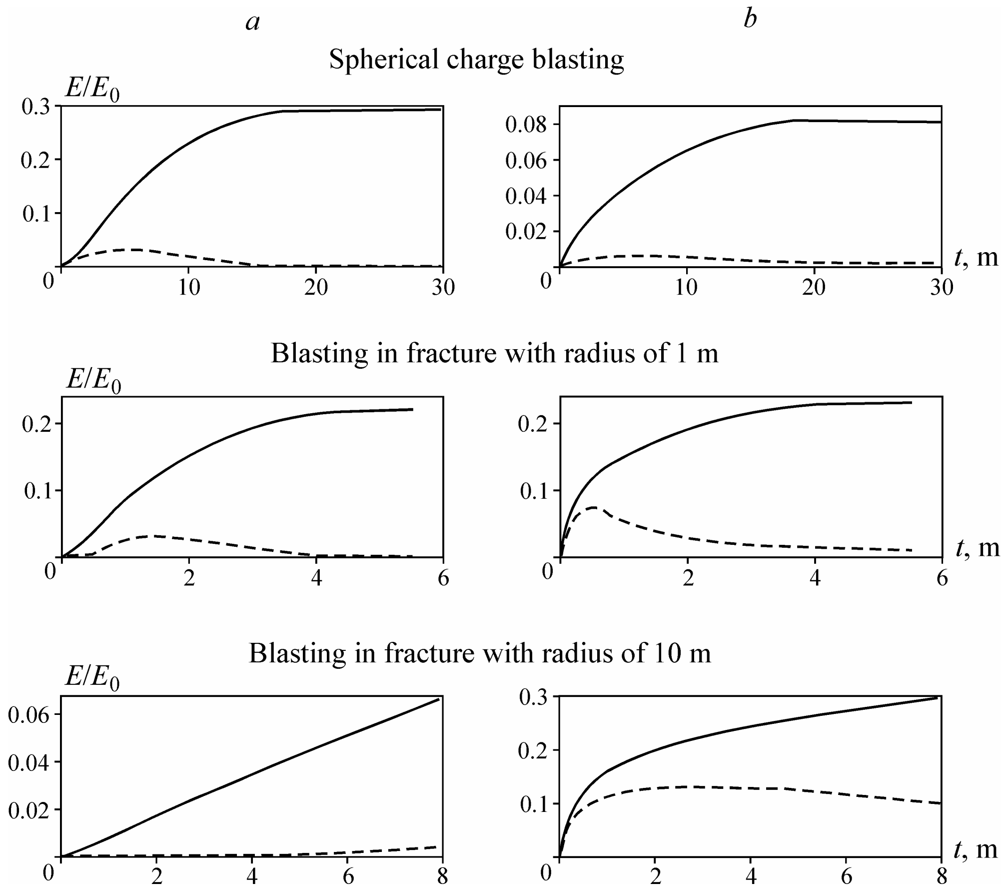

Fig. 8. Time-dependence of share of internal (solid line) and kinetic (dashed line) energy (*a*) in rock fracture zone and (*b*) beyond fracture zone

TABLE 1

Explosion type	Share of blast energy, %		
	transferred to soil	at fracture zone	beyond fracture zone
Spherical charge	37	29	8
Fracture 1 m in radius	46	22	24
Fracture 10 m in radius	50	10.6	39.4

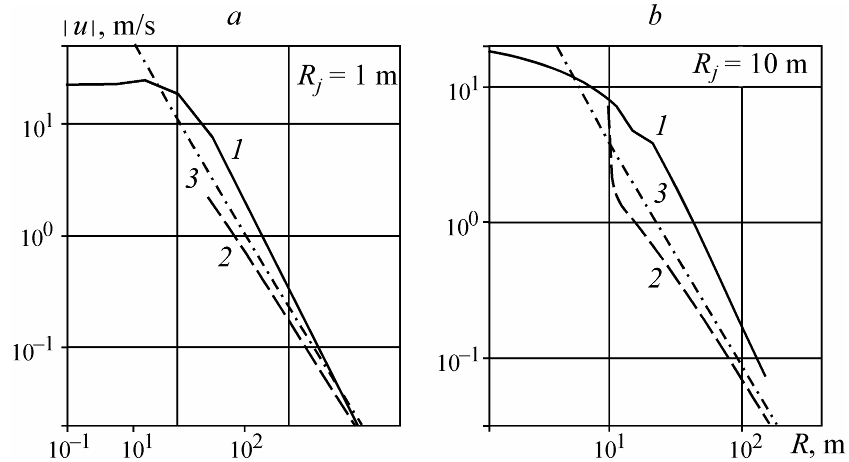

Fig. 9. Dependence of maximal soil movement velocity on distance: *1* — in perpendicular to the charge plane; *2* — in the direction lying in the plane of charge ($z = 0$); *3* — confined blasting of spherical charge

CONCLUSION

The studies showed that the interaction of seismic blast waves with geostructural disturbances in a rock mass is followed by the local changes in the wavefront shape and in the characteristics of the stress-strain state of rocks. This interaction may result in considerable alterations of the size and shape of the rock shear fracture. It should be kept in mind that not simply connected fracture zones may form in a rock mass, in this case, the rock fracture zones can alternate with the unbroken rock mass areas.

Thus, it can be concluded that it is not always correct to use the maximal medium movement velocity as a criterion of the rock fracture.

The influence of the seismic wavefront configuration on the rock fracture process is revealed in the case of the flat decked charge blasting effect on a rock mass, when the charge extension exceeds drastically the fracture zone size under the concentrated charge explosion of the same yield. The numerical modeling results showed that the seismic efficiency of the flat decked charges is considerably higher as compared to that of the concentrated charges of the same yield.

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