

CHANGE IN PROPERTIES OF GEOPHYSICAL MEDIUM DURING UNDERGROUND EXPLOSIONS

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Mechanisms of strength loss of rocks in a slightly fractured mass during confined explosions are considered. It is shown that, at small depth ($H \leq 400$ m) beyond the boundary of radial crack zone, local rock failure is possible under the action of hoop tensile stresses during a single explosion and under the action of shear stresses in wave superposition zones during a group explosion. At great depths, local failure and strength loss of rocks in the indicated area are possible by shear failure in zones of blast wave interaction.

In the last 10–15 years, there has been growing interest in the behavior of the geophysical medium and the irreversible change in its properties under action of underground explosion. This is connected with the development and application of nontraditional methods of carrying out blasting operations in geotechnological boreholes in order to increase their productivity [1, 2] and with the traditional use of powerful underground explosions for the solution of various problems in mineral prospecting, extraction, and storage [3].

In boundless mass, the basic change in the properties of medium around the explosion site is associated with intensive crushing and motion of the failed material in the grinding zone and with the formation of a system of radial cracks [4, 5]. However, irreversible changes in the properties of a medium undergoing brittle failure in the zone traditionally regarded as elastic are also of interest.

In [2, 6] and a number of studies of foreign researches, it has been shown that, under conditions of nonuniform three-dimensional dynamic and static compression at pre-limit loads, most of the rocks undergo irreversible changes in volume (dilatancy). The authors link this phenomenon with reorientation of the grains and the development of intergrain microcracking, as a result of which the rock structure loses its strength. Deformation process may also proceed in the opposite direction (the rock may be compacted [2]).

Most rocks representing the geophysical media are the materials with defects, among which the cracks are the most wide-spread defects. The length, number, and orientation of the cracks, which determine the strength and filtration properties of the medium, as well as the rock porosity under conditions of fluid saturation, may be very different. Thus, according to [7], the natural crack dimensions in geophysical medium range from a few millimeters to hundreds of meters or even first kilometers. The measure of action of blast waves after single or group explosions on such a medium and its new geomechanical properties beyond the bounds of the radial crack zone are determined by the dimensions of those defects and cracks, which were in the initial state in the medium and which varied their dimensions under the action of dynamic loads.

In [1], side by side with a crushing zone and a radial crack zone (RCZ), a local cracking zone is observed beyond the RCZ, extending to 1.7–2 RCZ radii, and is attributed to “failure of weak grains or expansion of the local weakening surfaces” [1].

To estimate the local crack formation beyond the bounds of RCZ in the presence of initial crack-type defects, it is of interest to use the mechanism of fracture mechanics.

We know that the dynamic failure of solid media may be described within a phenomenological or microstructural approaches [8]. According to the phenomenological approach, the rate of volume change of microdefects in the material is a function of the acting tensile stress σ or the pressure p and the quantity of microdefects in the microvolume ξ . According to the microstructural approach, the equation of microdefect origination and its evolution and coalescence with other defects are derived in the first stage. In the second stage,

statistical analysis is used to go from local to global failure characteristics and to describe the evolution of the statistical set of microdefects as a whole on the basis of the written equations of dynamics for individual components. In the third stage, a model of dynamic failure is constructed by comparing the experimental integral failure parameters with calculation results.

In evaluating the state of fracture mechanics for using its mechanism in the prediction of solid medium failure within the framework of microstructural approach, we may note that individual dynamic problems have been solved for single cracks by the present moment and there are a limited number of solutions for small groups of cracks (usually two) interacting with elastic waves.

Let us consider a slightly fractured nonblock geophysical medium with a characteristic dimension of the maximum cracks $l_0 < \lambda$ (λ is the wavelength of the blast wave). In natural conditions, this medium may be an oil or gas reservoir, a water-bearing formation, an ore body, gas cap and basement rocks of coal seams, the coal seam itself, and so on. In this connections, it is expedient to use an approximate approach based on analysis of the interaction of relatively long stress waves with short cracks and crack-like defects, at least, to estimate the critical parameters and the possibility of local failure of mass beyond the bounds of RCZ.

It is known that, with a single underground explosion, a compression wave arises around the explosion site [4, 5], and a shear wave appears when the first cracks develop at the borehole walls [9]. The wave pattern around the explosion site is complicated in the presence of the initial stresses. Theory predicts the appearance of an additional type of waves when a cylindrical charge explodes in a prestressed medium — in particular, a quasi-longitudinal or pure transverse wave with initial shear stresses of different intensity [10]. We also assume that the failure of most solid media in compression along the planes of the initial cracks sets in at a sufficiently high level of acting stresses, comparable with the shear modulus [11]. Evidently, therefore, the compression waves may not be the reason of local cracking, even during interaction of two underground explosions of chemical explosives and the presence of initial cracks in the interaction zone. This is confirmed in [12], where it is shown experimentally that the failure of K-8 glass begins when radial compressive stresses reach $\sigma_r^* = 4 \cdot 10^9$ Pa.

In a few studies devoted to the analysis of the stress-strain state of rocks during underground explosions, it has been shown that the tangential component of the stress becomes tensile on reaching a certain distance. According to [13], this distance is $14r_0$ (r_0 is the charge radius).

According to [1], the amplitude of the hoop tensile stresses σ_θ at the RCZ boundary is $(0.08-0.12)\sigma_c$ (σ_c is the uniaxial compression strength). According to [14], $\sigma_\theta = 6.3$ MPa when $r/r_0 = 18$, whereas $\sigma_\theta = 2.5$ MPa at the relative $r = 100$ in the explosion of a spherical charge in organic glass (OG).

This level of tensile stresses is quite sufficient to induce critical stresses at the crack contours located in the plane perpendicular (or close to it) to the direction of action of the dynamic stresses.

Using data on the attenuation of blast waves in rock masses, it is simple to determine the level of stresses σ_r at the RCZ boundary: $\sim 5.5 \cdot 10^7$ Pa in granite, $(1.9-2) \cdot 10^7$ Pa in hard limestones, and $(3-5) \cdot 10^6$ Pa in coquinas. These values amount to 10–25% of the corresponding dynamic ultimate strength in uniaxial compression σ_c [1]. At moderate depths of rock occurrence, the presence of initial cracks located in the radial and near to radial planes creates conditions for the initiation of these cracks by tensile stresses.

Let us write the conditions of local failure of medium.

With a quasi-static loading, i.e., when $c_1 t_- = \lambda \gg l_0$ (λ is the length of the blast wave in the tensile stress phase; t_- is the duration of the negative phase of the explosive pulse $\sigma_\theta(t)$; l_0 is the initial crack length; c_1 is the velocity of the longitudinal wave), the initiation condition of crack motion [15] can be described by relation

$$K_1 = K_{1C}, \quad K_1 = F_1 \sigma \sqrt{\pi l_0}, \quad (1)$$

where K_1 , K_{1C} are the stress intensity coefficient and crack resistance coefficient of the rock in separation failure; σ is the tensile stress; F_1 is the function depending on the form (geometry) of the initial crack and the form of the stress state.

On the basis of Eq. (1), taking account of the dynamics of failure process, we may write an expression for the critical failure stress σ_* of preliminarily loaded rock with an initial crack

$$\sigma_* = \frac{K_{1D}}{F_1 \sqrt{\pi l_0}} + q_\infty - p_f, \quad (2)$$

where K_{1D} is the dynamic failure viscosity; q_∞ is the value of rock pressure acting in the plane perpendicular to the crack plane; p_f is the intracrack formation fluid pressure. In particular, for a disk-shaped crack, Eq. (2) is transformed to the following form [16]

$$\sigma_* = \frac{K_{1D}}{2\sqrt{R_0/\pi}} + q_\infty - p_f. \quad (3)$$

For most wide-spread rocks, with $K_{1C} = (0.4 - 1.5) \cdot 10^6 \text{ MPa} \cdot \text{m}^{1/2}$, and short initial cracks (from a few cm to a few first tens of cm), Eq. (3) will be realized only when $q_\infty - p_f < \sigma_p$ (σ_p is the rock rupture ultimate strength), i.e., for occurrence depths $H \leq 200 - 500 \text{ m}$.

The dynamic failure viscosity K_{1D} differs from the static one K_{1C} , but for some rocks — for example, granite — the failure viscosity is practically independent of the loading rate [17]. Taking into account that t_- may reach $(0.4 - 0.6)t_+$, where t_+ is the duration of the compression phase of the pulse $\sigma_r(t)$, the described mechanism of rock failure is completely real. The more especially as such local mass failure is ensured not only by the tensile stresses σ_θ but also by the stresses σ_r compressing the rock along the plane where the initial crack is located [18]. This factor is probably the reason for the formation of local radial cracks considerably exceeding the mean RCZ dimension with single underground explosions in the rock mass [19] and also the increased crack porosity in group underground explosions [20].

However, there is another necessary condition for the initiation of transcritical development of each initial crack. It is associated with the existence of a critical time or period t_c of delay of crack initiation; t_c decreases with increase in the level of stresses acting on the crack contour and evidently depends on the properties of the material [21, 22]. According to the minimum time criterion proposed by Kalthoff and Shocki, crack initiation occurs when K_1 (the dynamic stress intensity coefficient) exceeds K_{1D} in a time $t_- \geq t_c$.

In [21] and in our previous studies, the results of numerical calculations of behavior of a plane crack of length l_0 and a disk-type crack of radius R_0 under the action of a rectangular tensile pulse of amplitude σ_0 and duration t_0 have been described. The wave front is parallel to the crack in both cases. The results may be used for qualitative analysis of the behavior of cracks of various sizes. They show that the minimum time criterion is wittingly satisfied for cracks of small size:

$$R_0 < (1/20)c_1 t_0 \text{ — for a disk-type crack} \quad (4)$$

$$l_0 < (1/40)c_1 t_0 \text{ — for a plane crack.} \quad (5)$$

It follows from Eqs. (4) and (5) that not any crack, that is beyond the RCZ, may be initiated by the tensile stress phase in the explosive pulse. Besides, we reach the practically important conclusion: the longer (in terms of the tensile stress phase t_-) explosive pulse involves more quantity of initial cracks and crack-like defects into the process of local crack formation, by two means: 1) the charge diameter increases when low explosives are used; 2) low-brisant explosives generate longer and more slowly increasing explosive pulses than high explosives.

Thus, we need to add the condition (3)

$$t_- > t_c \text{ or } c_0 t_- > ag,$$

where a is the crack geometry parameter; g is a numerical coefficient (close to 1) [21].

From Eq. (3), using the attenuation law of blast waves in rocks in the form $|\sigma_r| = k(r/r_0)^{-\mu}$, we may obtain a formula for the critical radius of a disk-shaped crack, which may be initiated by a stress pulse $\sigma_\theta = \alpha\sigma_r$ ($\alpha < 1$)

$$R^* = \pi K_{1D}^2 [-ak(r/r_0)^{-\mu} - q_\infty + p_f]^{-1/2}. \quad (6)$$

In contrast to the plastic zone, where $\alpha = 0.51$ according to [14, 23], $\alpha = 0.16 - 0.20$ for OG for relative distances $r/r_0 = 18 - 100$. The possibility of using these values for rocks requires experimental verification or theoretical analysis; therefore, the following calculations have an estimation character. Consider the case of marble. The initial data for the calculations are as follows: $K_{1C} = 0.58 \text{ MN/m}^{3/2}$; $K_{1D} = 2 - 2.5$; $K_{1C} = 1.16 - 1.45 \text{ MN/m}^{3/2}$; $p_f = 0$; $k = 6880 \text{ MPa}$; $\mu = 1.07$; $\alpha = 0.16$.

The calculations showed that the critical radius of the initial disk-shaped crack is $(0.13 - 3.82 \cdot 10^{-2}) \text{ m}$ for relative distances of $25 - 120 r_0$ in the absence of rock pressure. As the rock pressure increases, the local failure region is shifted toward the RCZ boundary and becomes narrower. Thus, when $q_\infty = 10 \text{ MPa}$,

$R^* = 0.0026-0.18$ m (for various values of K_{1D}) at relative distances of $25-60 r_0$. When $q_\infty = 15$ MPa, the critical radius is $0.0041-0.0046$ m for a relative distance of $25-50 r_0$. In the third case, when $r = 50 r_0$, local failure cannot occur, since the critical crack radius is comparable with the wavelength in the tensile stress phase $c_1 t_-$ and the minimum time criterion cannot be satisfied.

The brittle failure mechanics of materials with cracks also predicts the failure of bodies with shear stresses in the crack vicinity [15, 18]. Such a stress state in a separate part of rock mass may be created by the superposition of blast waves with a certain phase shift, for example. The limiting equilibrium condition of material with a disk-shaped crack under a quasi-static loading without initial stresses takes the form [15]

$$K_{11}^0 = [4\tau R^{0.5} / (2 - \nu)\pi^{0.5}] \cos(\theta - \beta) = K_{11C}, \quad (7)$$

$$K_{111}^0 = [-4(1 - \nu)\tau R^{0.5} / (2 - \nu)\pi^{0.5}] \sin(\theta + \beta) = K_{111C}, \quad (8)$$

where K_{11} , K_{111} are the stress intensity coefficients (SIC) of longitudinal and transverse shears, respectively; ν is Poisson's ratio; θ is the polar angle; β is the angle between the crack plane and the direction of action of the shear stresses; K_{11C} , K_{111C} denote the failure viscosity of the rock in longitudinal and transverse shear.

The parameter τ is determined by the difference between the maximum σ_1 and minimum σ_3 of normal stresses acting in the crack vicinity and may reach $100-400$ MPa with the superposition of blast waves in dense rocks [1]. There are practically no data on the parameters K_{11C} and K_{111C} for rocks and their dependence on the loading rate; however, by analogy with metals, for which $K_{11C} < 2K_{1C}$ [24], we may assume that K_{11C} and K_{111C} are of the same order as K_{1C} . Even under these assumptions, it is simple to make sure that at the contours of a disk-shaped crack, at the given stress level, in typical rocks (granite, sandstone, rock salt), within a certain sector of angle θ , conditions for limiting equilibrium of the medium with the crack and failures by longitudinal or transverse shear appear. Data on the crack resistance of the indicated rocks from [23] were used in estimating calculations.

SAMPLE CALCULATION

Consider granite with $K_{1C} = 1.17$ MN/m^{3/2}; $R^* = 0.1-0.2$ m, $\nu = 0.18$, and $K_{11C} = 2K_{1C}$. The results of calculation given by Eq. (7) show that the critical tangential stresses for transverse shear in the sector of angle $\theta - \beta = 0-85^\circ$ are $5.83-67.0$ MPa for $R = 0.1$ m and $4.24-48.7$ MPa for $R = 0.2$ m. Therefore, local failure of rock with the corresponding parameters of interacting charges is real. When $\beta = 0$ in the sector $\theta = 85-90^\circ$, under conditions of three-dimensional loading, the tangential stresses are small for the development of transverse shear failure but sufficient for longitudinal shear failure.

In a medium with initial stresses, the expressions for the SIC are analogous [18] but include coefficients depending on the level of initial stresses

$$K_{11} = K'' K_{11}^{(0)}, \quad K_{111} = K''' K_{111}^{(0)},$$

$$K'' = (2 - \nu) / (2 - \nu_1), \quad K''' = (2 - \nu)(1 - \nu_1) / (2 - \nu_1)(1 - \nu),$$

where ν_1 depends on the level of initial stresses; the dependences of K_{11} and K_{111} on the value of initial stresses, have complicated nature (the investigation of this nature is beyond the scope of the present work). There are values of the initial stresses corresponding to an unstable equilibrium position of the material, and slight change in the stress state is enough to disturb equilibrium [18]. We know that there is a set of initial stress states in the rock mass, including those in the vicinity of the mine working [24]. Therefore, we may suppose that, in the presence of initial stresses, prerequisites exist for the strength loss of rock mass with initial cracks in certain conditions by change in the crack dimensions (width and extent) under the action of dynamic shear stresses. The more preferable type of initial stress state here, evidently, is a nonuniform initial state with differing components of the initial stress tensor.

The interaction of compression-tension and shear waves with cracks is accompanied by dynamic phenomena, namely, crack growth when the wave is incident at the crack tip. Convincing results are obtained at plane samples for waves of all types, including Rayleigh waves [26]. Therefore, in the absence of initial stresses in the medium, change in dimensions of the relatively long initial cracks under the action of stress waves is possible, at least under conditions that are near to plane deformation, i.e., in the explosion of extended charges, and also in explosions of decked charges with ultrashort inhibition with respect to each other.

Since these strength loss and decompaction mechanisms of cracked rocks are completely real, we may speak not only of dilatancy of monolithic crystalline rocks at the microvoid level [1, 2] but also of strength loss of the rocks as a result of change in the parameters of the initial cracks of natural origin or cracks artificially created in the mass.

Some examples of strength loss of mass during blasting operations in [27] provide indirect confirmation of this.

Further experimental confirmation is provided by the results of injection well torpedoing in the eastern oil and gas fields of the Ukraine [27]. Operations carried out in the wells opening oil formations, that consist of fractured sandstones, showed an increase in well throughput by a factor of 3–6 at the same discharge pressures.

CONCLUSIONS

1. The possibility of irreversible changes in rock mass during an underground explosion in the region adjacent to the destroyed one has been analyzed. It is established that, besides a dilatancy mechanism of change in the properties of crystalline rocks in mass, there is another mechanism associated with the possibility of change in the parameters of initial fracturing of mass.

2. In the underground explosions of charges at shallow depths (up to 200–400 m), the rock properties in the explosion zone may change on account of increase in sizes of the existing initial cracks by the hoop tensile stresses in the region where the medium moves behind the front and as a result of critical conditions of shear at the contours of the initial cracks in the regions of blast wave superposition for group explosions.

3. At great depths, evidently, rock strength loss in shear stress regions may be expected when critical conditions of local transverse and longitudinal shear appear at the initial crack contours, as well as change in the initial crack dimensions occurs in the diffraction of short blast shear and compression waves at the contours of long initial cracks.

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