DIMENSIONS OF THE FAILURE ZONE IN THE FAILURE OF A GAS CAVITY IN A SATURATED BRITTLE-FRACTURABLE MEDIUM

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UDC 539.375.5−534.222

One of the main problems arising in studying the action of an underground explosion is determining the sizes of the failure zones. For explosions in a dry porous or monolithic medium, this problem has been investigated quite thoroughly and numerical as well as analytical results, connecting the dimensions of the failure zone with the characteristics of the medium and the parameters of the explosion, have been obtained (see, e.g., [1, 2]). At the same time, the action of an explosion of porous rock saturated with a liquid has been studied in less detail.

In the present work, we examine an underground explosion in saturated brittle-fracturable rock and estimate the dimensions of the failure zones formed.

Model of the Medium. Sedimentary rock (e.g., sandstone) consists of solid grains cemented together, the porous space between which can be filled with a liquid or gas. In studying the deformation of such rock, it is convenient to introduce an effective stress [3], which with a spherically symmetrical explosive motion and point contacts between grains has the form

$$\sigma_r^f = (1-m)(\sigma_r + p),\ \sigma_\varphi^f = (1-m)(\sigma_\varphi + p),$$

where σ_r and σ_φ are the radial and azimuthal stresses in the framework; p is the pressure of the interstitial liquid; m is the porosity.

As is well known, the effective stresses constitute that part of the stresses in the framework that is transmitted along the contacts between grains. And, since failure in the medium and plastic flow of the pulverized material also occur along the contacts between grains, according to Tertsag's principle, the criteria for failure and plastic flow, written for the effective stresses, have the same form as in unsaturated rock [3, 4]. The validity of such an assumption is supported by the experimental work [5-8]. The condition for the appearance of a zone with numerous radial cracks (R zone) in this case is written in the form

$$\sigma_\varphi^f = \sigma_0, \tag{1}$$

while the criterion for shear failure (splitting) [9] is

$$|\sigma_\varphi^f - \sigma_r^f| = \sigma_s + 3k_s\sigma^f, \tag{2}$$

where $\sigma' = -(\sigma_r^f + 2\sigma_\varphi^f)/3$ is the effective pressure; σ_s and k_s are coefficients. The condition for plastic flow in the crushed zone (C zone) is

$$|\sigma_\varphi^f - \sigma_r^f| = 3k\sigma^f, \tag{3}$$

where k is the coefficient of friction of the crushed material. The loss of strength by the medium in the azimuthal direction in the R zone is characterized by the absence of any transmission of energy in the framework along the contact in this direction, which is written in the form

$$\sigma_\varphi^f = 0. \tag{4}$$

In addition, we will assume that at the time of the explosion there is no drainage. Then, in regions where the volume deformation occurs elastically, it is possible to establish a relation between the change in interstitial pressure with the change in pressure in the framework. According to Bishop's model [10],

$$\frac{dp}{d\sigma} = \frac{c-(1-m)c_s}{mc_F + c - (1-m)c_s},$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 119-126, March-April, 1981. Original article submitted February 28, 1980.

0021-8944/81/2202-0241$07.50

where c, c_S, and c_F are, respectively, the compressibility of the framework, the solid material of the grains, and the liquid. If we limit ourselves to the case

$$c-(1-m)c_s \ll mc_F + c - (1-m)c_s,$$

then $dp/d\sigma \ll 1$, the effect of the change in the interstitial pressure can be neglected, and it may be assumed that $p \approx$ const.

Thus, in examing the problem of an explosion we will assume that in the elastic deformation zone (E zone) and in the R zone, where the volume deformation is elastic, the pressure remains constant. The problem is more complicated in the C zone, where a plastic change in the volume is possible under shear, dilatancy [11]. In order to describe the C zone, we will examine two limiting cases: 1) dilatancy is absent, volume deformations are elastic, and $p \simeq$ const; 2) dilatancy loosening leads to a large increase in the pore volume, and the pressure of the liquid in this case drops to zero ($p=0$).

Equation of Wavefree Dynamics in the Absence of Dilatancy. Let us first consider the case when there is no dilatancy in the C zone and $p \simeq$ const everywhere outside the cavity and throughout the duration of the explosion. In this case, from the equation of continuity in the approximation of wavefree dynamics (density ρ=const) [1, 2] it follows that the velocity distribution is $v(r)=\dot{a}a^2/r^2$, where $a(t)$ is the radius of the cavity, $\dot{a}=da/dt$. Substituting $v(r)$ into the equation of motion, we obtain an equation for the effective stresses

$$\rho\left[\frac{1}{r^2}\frac{d}{dt}(\dot{a}a^2)-\frac{2a^4\dot{a}^2}{r^5}\right]=\frac{\partial\sigma_r^f}{\partial r}+\frac{2\left(\sigma_r^f-\sigma_\varphi^f\right)}{r}, \tag{5}$$

similar to the equation for a dry medium.

From Eq. (5), using criteria (3) and (4) and Hooke's law in the convective form for differential stresses in the E zone [1]*

$$\dot{\sigma}_\varphi^f-\dot{\sigma}_r^f=2G\left(\frac{\partial v}{\partial r}-\frac{v}{r}\right), \tag{6}$$

where G is the shear modulus for the framework, we obtain the stress distribution in each of the zones. By requiring that the failure criteria (1) and (2) be satisfied on approaching the corresponding zone from the large r side and that the conditions of continuity of σ_r^f at the zone boundaries be satisfied, we obtain the camouflet equations determining the radii of the failure zones

$$\begin{gathered}
\sigma_0+p_c^f-2G\frac{a^3-a_0^3}{3b_0^3}+\rho\left[\frac{1}{b_0}\frac{d}{dt}(\dot{a}a^2)-\frac{a^4\dot{a}^2}{2b_0^4}\right]=0,\\
\sigma_{s1}-(p_a-p)\frac{a^\beta}{b^\beta}+\rho\left[\frac{2\dot{a}^2}{4-\beta}\left(\frac{a^4}{b^4}-\frac{a^\beta}{b^\beta}\right)-\frac{1}{1-\beta}\left(\frac{a}{b}-\frac{a^\beta}{b^\beta}\right)\frac{d}{dt}(\dot{a}a^2)\right]=0,\\
\sigma_0+\sigma_{s1}\frac{b^2}{b_0^2}-2G\frac{a^3-a_0^3}{b_0^3}+\rho\left[\frac{a^4\dot{a}^2(b_0^2-b^2)}{b_0^4b^2}-\frac{(b_0-b)}{b_0^2}\frac{d}{dt}(\dot{a}a^2)\right]=0,
\end{gathered} \tag{7}$$

where $p_c^f=(1-m)(p_c-p)$ is the effective background pressure; p_c is the background pressure in the framework; a_0 is the starting radius of the cavity; b and b_0 are the radii of the C and R zone boundaries, respectively; p_a is the pressure in the cavity; $\beta=6k/(1+2k)$; $\sigma_{s1}=\sigma_s/(1-k_s)$.

If the R zone is absent, then the camouflet equations have the form

$$\begin{gathered}
\sigma_s+3k_sp_c^f-2G\frac{a^3-a_0^3}{b^3}+3k_s\rho\left[\frac{1}{b}\frac{d}{dt}(\dot{a}a^2)-\frac{a^4\dot{a}^2}{2b^4}\right]=0,\\
p_c^f-(p_a-p)\frac{a^\beta}{b^\beta}+4G\frac{a^3-a_0^3}{3b^3}+\rho\left[\frac{\dot{a}^2}{2(4-\beta)}\left(\beta\frac{a^2}{b^4}-4\frac{a^\beta}{b^\beta}\right)-\frac{1}{1-\beta}\left(\beta\frac{a}{b}-\frac{a^\beta}{b^\beta}\right)\frac{d}{dt}(\dot{a}a^2)\right]=0.
\end{gathered} \tag{8}$$

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*In the general case, in order to describe the deformations of saturated media the generalized Hooke's law [12] or the effective stresses in Biot's form [5] should be used. However, in order to simplify in the present work, we will limit ourselves to using the effective stresses in Tertsagi's form, since it is this particular form that best determines the limiting state of the medium [3-5] and, therefore, the dimensions of the failure zones.

It is evident from (7) and (8) that the nonzero pressure of the saturating liquid leads, in comparison to dry rock (p = 0), to a decrease in the effective background pressure p_c^f and partial neutralization of the pressure in the cavity. Assuming that $\dot{a} = 0$ and eliminating $\ddot{a}$ from the system of equations (7) or (8), we find a relation between the maximum dimensions of the failure zone b_m, b_{0m} and the maximum dimension of the cavity. If $\beta = 1\ (\sigma_r^f = 2\sigma_\varphi^f)$ [2], $(p_a - p)a_m/b_m \ll \sigma_{s1}$, and $|\ln(b_m/a_m) - 1|b_m/b_{0m} \ll 4$, then

$$b_{0m}^3 = \frac{8Ga_m^3}{3\left(2\sigma_0 + p_c^f\right)}, \quad b_m = \frac{\alpha\left(2\sigma_0 + 3p_c^f\right)}{4\sigma_{s1}} b_{0m}, \quad \alpha = \ln\frac{b_m}{a_m} \sim 2 \tag{9}$$

or, in the absence of an R zone,

$$b_m^3 = \frac{2G(1 + 2k_s)}{\sigma_s} a_m^3. \tag{10}$$

Here b_m/a_m increases with k_s due to the effect of inertia, which predominates over the decrease in b_m/a_m due to the increase in strength $\sim \sigma_s + 3k_s p_c^f$.

If we set $\dot{a} = 0$ and $\ddot{a} = 0$, then we obtain the equilibrium quasistatic dimensions of the failure zone b_{0e}, b_e and the cavity a_e

$$b_{0e}^3 = \frac{2Ga_e^3}{3\left(\sigma_0 + p_c^f\right)}, \quad b_e^2 = \frac{2\sigma_0 + 3p_c^f}{\sigma_{s1}} b_{0e}^2, \quad \frac{a_e^{3\gamma}}{a_0^{3\gamma}} = p_0\left\{p + \left[\frac{2G}{3\left(\sigma_0 + p_c^f\right)}\frac{b_e^3}{b_{0e}^3}\right]^{\frac{\beta}{3}}\sigma_{s1}\right\}^{-1} \tag{11}$$

or, in the absence of an R zone,

$$b_e^3 = \frac{2Ga_e^3}{\sigma_s + 3k_s p_c^f}, \quad \frac{a_e^{3\gamma}}{a_0^{3\gamma}} = p_0\left\{p + \frac{b^\beta}{a^\beta}\left[p_c^f + \frac{2}{3}(\sigma_s + 3k_s p_c^f)\right]\right\}^{-1}. \tag{12}$$

In obtaining (11) and (12), it was assumed that the gas in the cavity expands adiabatically with an adiabatic index γ: $= p_a = p_0(a_0/a)^{3\gamma}$, where p_0 is the initial pressure in the cavity.

<u>Taking into Account Dilatancy in the Crushed Zone.</u> In taking into account the loosening up due to dilatancy in the crushed zone, we will assume that the pressure of the liquid is p = 0. This assumption is justified by the fact that the change in the pore volume with dilatancy can be large and the liquid pressure in this case drops rapidly to zero.

With a constant dilatancy rate Λ in the approximation of elastic incompressibility of the medium, the velocity has the following form as a function of radius [2]:

$$v(r) = \begin{cases} \dot{a}a^n/r^n, & a < r < b, \\ \dot{a}a^n b^{2-n}/r^2, & r > b, \end{cases}$$

where $n = (2 - \Lambda)/(1 + \Lambda)$. Knowing v(r), from the equations of motion taking into account Eqs. (1)-(4) and (6) and the conditions of continuity of the radial stresses $\Gamma_r = (1 - m)\sigma_r - mp$, we find the camouflet equations

$$\begin{gathered}
\sigma_0 + p_c^f - \frac{2GS(t)}{b_0^3} + \frac{\rho}{b_0}\left[\frac{d}{dt}\left(a^n b^{2-n}\dot{a}\right) - \frac{a^{2n}b^{4-2n}\dot{a}^2}{2b_0^3}\right] = 0, \\
\sigma_{s1} + p - p_a\frac{a^\beta}{b^\beta} + \rho\left[\frac{a\ddot{a} + n\dot{a}^2}{1 + \beta - n}\left(\frac{a^{n-1}}{b^{n-1}} - \frac{a^\beta}{b^\beta}\right) - \frac{n\dot{a}^2}{2n - \beta}\left(\frac{a^\beta}{b^\beta} - \frac{a^{2n}}{b^{2n}}\right)\right] = 0, \\
\sigma_0 + \sigma_{s1}\frac{b^2}{b_0^2} - \frac{6GS(t)}{b_0^3} + \rho\frac{(b_0 - b)}{b_0^2}\left[\frac{a^{2n}\dot{a}^2(b_0 + b)}{b_0^2 b^{2n-2}} - \frac{d}{dt}\left(a^n b^{2-n}\dot{a}\right)\right] = 0, \\
S(t) = \int_0^t a^n b^{2-n}\dot{a}\,dt.
\end{gathered} \tag{13}$$

If the R zone is absent, then

$$\begin{gathered}
\sigma_s + 3k_s p_c^f - \frac{6GS}{b^3} + \frac{3k_s\rho}{b}\left[\frac{d}{dt}\left(a^n b^{2-n}\dot{a}\right) - \frac{a^{2n}\dot{a}^2}{2b^{2n-1}}\right] = 0, \\
p + p_c^f - p_a\frac{a^\beta}{b^\beta} + \frac{4GS}{b^3} - \rho\left\{\dot{a}^2\left[\frac{\beta}{2(\beta - 2n)}\frac{a^{2n}}{b^{2n}} - \frac{n(2 + \beta - n)}{1 + \beta - n}\frac{a^{n-1}}{b^{n-1}}\right.\right. \\
\left.\left. + \frac{n(1 + n)a^\beta/b^\beta}{(1 + \beta - n)(2n - \beta)}\right] - a\ddot{a}\left(\frac{2 + \beta - n}{1 + \beta - n}\frac{a^{n-1}}{b^{n-1}} - \frac{a^\beta/b^\beta}{1 + \beta - n}\right) - (2 - n)\dot{a}\dot{b}\frac{a^n}{b^n}\right\} = 0.
\end{gathered} \tag{14}$$

From the system of equations (13) and (14), it is possible to obtain the equilibrium quasistatic dimension of the failure zones. Thus, from (13) with $\dot{a}=0$ and $\ddot{a}=0$, it follows that

$$b_e^{\beta}=\frac{p_0 a^{\beta}}{\sigma_{s1}+p},\quad b_{0e}^{2}=\frac{\sigma_{s1} b_e^{2}}{2\sigma_0+3p_c^f}. \tag{15}$$

If it is assumed that the asymptotic relation $2GS=(\sigma_0+p_c^f)b_0^3$ following from the first equation of the system (13) is valid, beginning with the dimensions of the cavity and the C zone a_1, b_1 such that $a_e \gg a_1$ and $b_e \gg b_1$, then in addition to (15) we obtain the relation

$$b_e^{n+1}=\left(\frac{2\sigma_0+3p_c^f}{\sigma_{s1}}\right)^{\frac{3}{2}}\frac{2Ga_0^{n+1}}{3(\sigma_0+p_c^f)}, \tag{16}$$

which leads to the equilibrium cavity size

$$\frac{a_e^{3\gamma}}{a_0^{3\gamma}}=\frac{p_0}{\sigma_{s1}+p}\left[\frac{3(\sigma_0+p_c^f)}{2G}\frac{b_{0e}^3}{b_e^3}\right]^{\frac{\beta}{1+n}}.$$

In the case that the R zone is absent, it follows from (14) with $\dot{a}=0$ and $\ddot{a}=0$ that

$$b_e^{n+1}=\frac{2Ga_e^{n+1}}{\sigma_s+3k_s p_c^f},\quad \frac{a_e^{3\gamma}}{a_0^{3\gamma}}=\frac{p_0\left[(\sigma_s+3k_s p_c^f)/2G\right]^{\frac{\beta}{n+1}}}{\left[\frac{2}{3}(\sigma_s+3k_s p_c^f)+p+p_c^f\right]}. \tag{17}$$

Statistical Estimate of the Size of the Mainline Crack in the Elastic Zone. In the elastic zone, there is no failure, but it is possible for individual mainline cracks to appear. It is well known from experiment that several cracks appear in the elastic zone, but for estimates we will assume that there is only one disk-shaped radial crack beginning at the boundary of the failure zone. Its size in the static approximation can be found from the theory of cracks [3], using the relation

$$K\sqrt{\frac{l}{\pi}}=\int_R^l \frac{r\sigma_\varphi^f(r)\,dr}{\sqrt{l^2-r^2}},$$

where l is the radius of the crack; R is the boundary of the failure zone (b_0 or b); K is the critical coefficient for the stress intensity.

If the E zone is next to a R zone, then $R=b_0$ and the size of the mainline crack is determined by the equation

$$K\sqrt{\frac{L}{\pi b_0(L^2-1)}}=-p_c^f+\frac{\sigma_0+p_c^f}{L^2}, \tag{18}$$

where $L=l/R$. For rocks, $K<10^2$ kgf/cm$^{3/2}$ (e.g., for limestone $K=20$–40 kgf/cm$^{3/2}$ [14]) and with $\sigma_0 \sim 10^1$ bar, $b_0 \sim 10^2$ m the coupling term can be neglected [15] over a wide range of values of L and it is possible to use the approximate formula

$$L^2=1+\sigma_0/p_c^f. \tag{19}$$

In the case that the R zone is absent, the size of the crack is found from the equation

$$K\sqrt{\frac{L}{\pi b(L^2-1)}}=-p_c^f+\frac{\sigma_s+3k_s p_c^f}{3L^2}, \tag{20}$$

or

$$L^2=k_s+\sigma_s/3p_c^f. \tag{21}$$

It is clear that the mainline crack in this case is absent for $\sigma_s<3p_c^f(1-k_s)$. The relative size of the crack L, as follows from (19), (21), depends weakly on the size of the failure zone. In addition, one should note that since the horizontal stress in the layer is usually less than the vertical stress [15] and is more easily compensated by the interstitial pressure, it is easier for the vertical crack to appear.

The dependence of L as a function of p for an explosion in rock with parameters $m=0.1$, $k_s=0.23$, $\sigma_s=40$ bar, $p_c=250$ bar (curve 1) and $m=0.1$, $k_s=0.33$, $\sigma_s=100$ bar, $p_c=600$ bar (curve 2) is shown in Fig. 1. The crack forms with $p>0.9p_c$ (curve 1) and $p>0.7p_c$ (curve 2) and its size increases rapidly with increasing p.

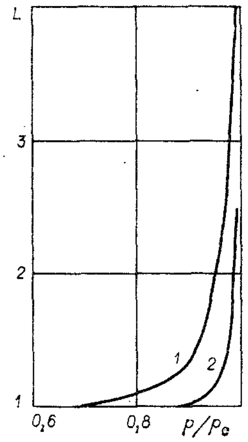

Fig. 1

For $p \approx p_c$, the size of the crack found from the static equations (18)-(21) turns out to be anomalously large. In this connection, it should be noted that in reality there are phenomena that impede and stop the growth of cracks. For example, these include simultaneous appearance of several cracks, cessation of growth as a result of interaction with defects in the medium, the finite rate of filtration of the liquid into the crack.

Discussion. Based on the equations obtained for the dimensions of the failure zones and the length of the mainline crack, we will examine qualitatively the effect of the saturating liquid on explosion-induced failure. First of all, the interstitial fluid has an effect through its pressure. The pressure enters into the asymptotic equations (9)-(12), (15)-(17) for b, b_0 and Eqs. (18)-(21) for L primarily through the effective pressure p_c^f, and its effect consists in compensating the background pressure of the framework. In accordance with (9)-(12), (15)-(21) this leads to large failure zone dimensions and a long mainline crack in comparison with an explosion in dry rock, where $p = 0$. Thus, an underground explosion at some depth with a background pressure in the framework of p_c and interstitial pressure p is in some sense equivalent to an explosion at a smaller depth with background pressure $p_c - p$ and zero interstitial pressure.

The growth of the failure zone with an explosion in saturated rock in comparison to an explosion in dry rock with other conditions remaining the same can be significant. Indeed, the strength constants of rocks can be σ_0, $\sigma_s \sim 10^1$ bar, $k_s \sim 1/3$ [2, 9], and the lithostatic pressure at depths of about a kilometer constitute $p_c \sim 10^2$ bar. For this reason, with an explosion in dry rock, the dimensions of the failure zone are determined by the background pressure. If, on the other hand, the explosion occurs in saturated rock, when p_c to a large extent is compensated by the pressure of the liquid in the layer ($p \approx p_c$), then the dimensions of the failure zones will already be determined by the strength characteristics of the medium σ_0, σ_s and can increase strongly, if σ_0, $\sigma_s \ll p_c$. In this case, the length of the mainline crack can increase to an even greater extent [see (18)-(21) and Fig. 1].

Let us consider the possibility of such compensation of the background pressure of the framework by the pressure of the fluid in the layer. If it is assumed that p coincides with the hydrostatic pressure $\rho_F gh$ (ρ_F is the density of the fluid, h is the depth at which the layer is located, g is the acceleration of gravity), then $p \sim p_c/3$ for $\rho_F = 1$ g/cm^3 and medium density of $\rho = 2.5$-3 g/cm^3. In this case there will be no noticeable compensation of the background pressure and the effect of p will be small. However, it is necessary to take into account the following two circumstances, which actually can lead to greater compensation. As experience shows, the interstitial pressure can exceed the hydrostatic pressure [16] and, in some cases, even the background pressure of the rock [17]. In addition, if the vertical pressure in the framework coincides with the lithostatic pressure ρgh, then the horizontal pressure can be less [15] and, therefore, it is more easily compensated. It should be noted that such stress anisotropy in the framework creates favorable conditions for growth of the failure zone in the horizontal direction and of mainline cracks in the vertical direction.

Another effect that also leads to a growth of failure zone is the decrease in the strength of the rock when it is saturated with liquid. It turns out that in this case σ_0 and σ_s can decrease by tens of percent [18, 19]. This, apparently, is related to the interaction of the saturating fluid and the framework, leading to a decrease in the surface failure energy. It is possible that as p increases this interaction will increase and the strength constants will decrease even further.

Let us find the condition for applicability of wavefree dynamics. In solving the problem of an explosion in the wavefree approximation, dissipative energy losses at the shock-wave front are not taken into account.

These losses can be estimated by considering the shock wave as a weak, i.e., using the adiabatic equation of state for cold compression in the relation of the pressure σ and specific volume of the medium V at the wave front [20]:

$$\sigma = A\left(V_0^i/V^i - 1\right), \quad A, \ i = \text{const.}$$

Then, the specific energy dissipated at the wave front (the pressure of the medium in front of the wave is not taken into account) [20] is

$$\Delta\varepsilon = \frac{1}{2}\sigma(V_0 - V) - \int_V^{V_0} \sigma dV.$$

If it is assumed that the compression in the wave is low $\Delta V = V_0 - V \ll V_0$, then

$$\Delta\varepsilon = (1 + i)V_0 c^2 \sigma^3/12,$$

where $c = 1/Ai$ is the compressibility of the medium. The total loss of energy on heating in the shock wave as it moves from the initial radius of the cavity is

$$E_T = \frac{\pi(1+i)c^2}{3}\int_{a_0}^{\infty} \sigma^3 r^2 dr.$$

Let the intensity of the shock wave decrease as a power of the distance as $\sigma = p_0 a_0^{\delta}/r^{\delta}$. Then

$$E_T = \pi(1 + i)c^2 p_0^3 a_0^3/9(\delta - 1),$$

i.e., the losses to dissipation are greater for media with greater compressibility. This, in particular, supports the numerical results of the work in [21]: In a water-saturated medium, the dimension of the plasticity zone is greater than in a gas-saturated medium. The authors of [21] relate this phenomenon to the smaller compressibility of the water-saturated medium (in comparison with the unsaturated medium), leading to a lower dissipation on the shock-wave front.

The energy of the explosion E_0 is determined by the initial energy of the gas in the cavity $E_0 = 4\pi a_0^3 p_0/3(\gamma - 1)$. For applicability of the wavefree approximation, it is necessary that $E_T \ll E_0$ or

$$p_0^2 \ll \frac{12(\delta - 1)}{(i + 1)(\gamma - 1)c^2}. \tag{22}$$

Thus, for $\delta = 2$, $i = 4$, $\gamma = 1.5$ Eq. (22) gives $p_0^2 \ll 10c^{-2}$.

The results obtained indicate the possibility of a strong effect of the saturating liquid on the dimensions of the failure zone and the appearance of the mainline cracks. This can lead to the formation of a large zone with increased permeability with a camouflet explosion in saturated medium as compared to an explosion in dry rock.

However, it should be noted that a complete and consistent theory of failure in a saturated medium (especially the formation of mainline cracks) must take into account the appearance of filtration of the interstitial fluid. For this reason, the approach used in the present work, naturally, is only approximate.

The author is grateful to E. E. Lovetskii and V. S. Fetisov for their attention to the work and for useful discussions, as well as V. G. Grigor'ev and B. M. Tulinov for useful suggestions.

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