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ROCK FAILURE

INFLUENCE EXERTED BY GAS LEAKAGES FROM THE EXPLOSION CAVITY FOR A SPHERICAL CHARGE ON ROCK BREAKING

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A calculated scheme is developed for the explosion action of a spherical charge in brittle rock taking account of the ejection of stemming and penetration of gaseous detonation products through the charge borehole into broken rock mass. The influence of stemming parameters on operating efficiency is determined. Estimates are given for the dimensions of breaking zones when the gas finds its way into cracks.

One of the aims of applying stemming during blasting of rocks is to retain the gaseous detonation products in the explosion cavity and to increase their work in crushing. In order to design the construction of a spherical charge with stemming it is necessary to calculate their interaction during an explosion. This problem is studied in the present work. Models are used for the works: in order to describe the ejection of stemming [1], and in order to calculate the action of the explosion of a concentrated charge [2, 3]. Wave processes in the gas are not considered. It is assumed that gas pressure varies quasi-statically with time according to an adiabatic rule for outflow from the borehole. Penetration of gases into the medium is assumed to be isothermal. One-dimensional equations describing centrally-symmetrical movement of the medium are used in calculating the dynamics of rock deformation and failure.

STATEMENT OF THE PROBLEM WITHOUT GAS PENETRATION INTO THE MEDIUM

In an unbounded elastic half-space an explosive charge is placed in a spherical cavity of radius a_0 connected to the day surface of a borehole with length l_z and radius a_{00} (Fig. 1). As a result of an explosion the cavity is filled with gases whose pressure is calculated by a modified Jones – Miller adiabat for a trotyl charge

$$p(\hat{\rho}) = \begin{cases} p_0(\hat{\rho}/\hat{\rho}_0)^{\gamma_1} & \hat{\rho} \ge \hat{\rho}_*, \\ p_0(\hat{\rho}_*/\hat{\rho}_0)^{\gamma_1}(\rho/\hat{\rho}_*)^{\gamma_2} & \hat{\rho} \le \hat{\rho}_*, \end{cases} \tag{1}$$

where $\hat{\rho}_* = 0.28\hat{\rho}_0$, $\gamma_1 = 3$, $\gamma_2 = 1.27$, $\rho_0 = 10^{10}$ Pa, $\hat{\rho} = \hat{\rho}(t)$ is gas density at instant of time t, $\hat{\rho}_0$ is the initial gas density in the explosion cavity [4]. By $\hat{\rho} = M/W$ we understand the average density determined from gas mass $M(t)$ and explosion cavity volume W.

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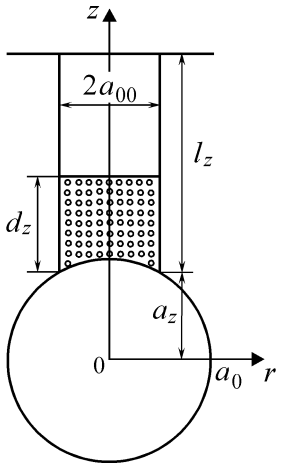

Fig. 1

After charge detonation elastic disturbance fronts of shear crushing and radial cracks go out successively into the rock. Simultaneously a packing wave propagates through the stemming, which is normally created from loose material. When the stemming is compacted over its whole length, there is ejection of it from the borehole and gas outflow into the atmosphere. We consider the processes that occur in the rock and the ejection of stemming separately.

DYNAMICS OF ROCK BREAKING

A version is analyzed where the crushing wave has less velocity than the elastic wave [3]. Three periods are separated in development of the explosion.

1. Solely elastic wave propagation until at the boundary $r = a(t)$ the breaking condition is fulfilled (r is current radius, $a(t)$ is explosion cavity radius).

2. The crushing wave moves with a velocity exceeding the maximum crack propagation velocity $V_{\max}$, and the deformation region is partitioned into two: shear crushing ($a(t) \le r \le b(t)$) and elastic ($r \ge b(t)$), where $b(t)$ is the boundary of transition from the crushing to the fracturing.

3. This stage commences when the condition $\dot{b} \le V_{\max}$ is fulfilled. A radial crack zone appears $b(t) \le r \le l(t)$. Here, $l(t)$ is crack front radius. In the region $r \ge l(t)$ rock deforms elastically.

The authors calculated the first two periods from the model described in [2, 3]. In the crushing zone the medium was assumed to be incompressible and (with deformation) it satisfies the Coulomb – Mohr condition.

In contrast to [3] the third period of radial crack system development is examined in a dynamic statement for the radial crack and elasticity zones.

Concerning $a(t)$ and $V(t) = \dot{a}(t)$ we have a set of first-order ordinary differential equations [3]:

$$\frac{da}{dt} = V, \qquad \frac{dV}{dt} = \frac{p(\hat{\rho}) - K_3 - 2V^2(K_1 - K_2)}{aK_1},$$

$$K_1 = \frac{\rho}{g-1}\left[\left(\frac{b}{a}\right)^{g-1} - 1\right], \qquad K_2 = \frac{\rho}{g-4}\left[\left(\frac{b}{a}\right)^{g-4} - 1\right], \tag{2}$$

$$K_3 = \left(\frac{Y}{\alpha} - q_b\right)\left(\frac{b}{a}\right)^{g} - \frac{Y}{\alpha}, \qquad q_b = \sigma_r(b+0), \qquad g = \frac{2\alpha}{1+\alpha},$$

$$Y = 2C\cos\varphi/(1-\sin\varphi), \qquad \alpha = 2\sin\varphi/(1-\sin\varphi),$$

C is adhesion coefficient, φ is the friction angle for crushed medium. Movement in a spherical coordinate system (r, θ) in the crack zone is described by an equation [5]:

$$\frac{\partial^2 u^c}{\partial t^2} = c^2 \left(\frac{\partial^2 u^c}{\partial r^2} + \frac{2}{r}\frac{\partial u^c}{\partial r} - \frac{2P(1-2\nu)}{Er} \right), \qquad c = \sqrt{\frac{E}{\rho}},$$

here, u^c is radial displacement (we shall designate values relating to the rod zone with index "c"), E is Young's modulus, ρ is medium density, P is rock pressure, ν is Poisson's ratio. The solution of this equation is as follows:

$$u^c = \frac{f_1(ct+r)}{r} + \frac{f_2(ct-r)}{r} + \frac{P(1-2\nu)r}{E},$$

where f_1 and f_2 are unknown functions. In the elasticity zone medium movement is described by a wave equation with respect to radial displacement u supplementary to the initial displacement

$$\frac{\partial^2 u}{\partial t^2} = c_p^2 \left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2} \right), \qquad c_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \tag{3}$$

c_p is longitudinal wave velocity in elastic medium. The general solution of this equation is

$$u = \frac{f'(c_p t - r)}{r} + \frac{f(c_p t - r)}{r^2}, \tag{4}$$

f is an unknown function. Assuming that at the boundaries $r = b(t)$ and $r = l(t)$, continuity conditions for stresses σ_r, displacements u, and velocities $\dot{u}$ are fulfilled

$$\sigma_r(b-0) = \sigma_r^c(b+0), \qquad \dot{u}^c(b+0) = \dot{a}\left(\frac{a}{b}\right)^2, \tag{5}$$

$$\sigma_r^c(l-0) = \sigma_r(l+0), \qquad u^c(l-0) = u(l+0), \qquad \dot{u}^c(l-0) = \dot{u}(l+0). \tag{6}$$

As calculations showed, this simplification is valid with a small change in medium density during breaking [3]. Conditions (5) and (6) serve for determining functions f, f_1, and f_2 in the third period:

$$\sigma_r^c(b+0) = E\left(\frac{f_1'(ct+b)}{b} - \frac{f_1(ct+b)}{b^2} - \frac{f_2'(ct-b)}{b} - \frac{f_2'(ct-b)}{b^2} \right),$$

$$f_1'(ct+b) + f_2'(ct-b) = \frac{\dot{a}a^2}{cb},$$

$$\frac{f_1'(ct+l)}{l} - \frac{f_1(ct+l)}{l^2} - \frac{f_2'(ct-l)}{l} - \frac{f_2(ct-l)}{l^2} =$$

$$= -\frac{P}{E} - \frac{2}{1+\nu}\left(\frac{f'(c_p t-l)}{l^2} + \frac{f(c_p t-l)}{l^3} \right) - \frac{c_p^2}{c^2}\frac{f''(c_p t-l)}{l}, \tag{7}$$

$$f_1(ct+l) + f_2(ct-l) + \frac{P(1-2\nu)l^2}{E} = f'(c_p t-l) + \frac{f(c_p t-l)}{l},$$

$$f_1'(ct+l) + f_2'(ct-l) = \frac{c_p}{c}\left(f''(c_p t-l) + \frac{f'(c_p t-l)}{l} \right).$$

We designate the following: $\varphi(t) = f(c_p t - l(t))$, $\phi(t) = f'(c_p t - l(t))$, $\phi_1(t) = f_1'(ct + l(t))$, and $\phi_2(t) = f_2'(ct - b(t))$. Then in order to determine functions φ, ϕ, ϕ_1, and ϕ_2 taking account of (7), we obtain

$$\frac{d\varphi}{dt} = (c_p - \dot{l})\phi, \quad \frac{d\phi}{dt} = (c_p - \dot{l}) f''(c_p t - l) = (c_p - \dot{l})\left[\frac{c}{c_p}(\phi_1(t) + \phi_2(t - t_*)) - \frac{\phi(t)}{l}\right],$$

$$\phi_1(t) = \left[F(t) + \phi_2(t - t_*)\left(1 - \frac{c_p}{c}\right)\right]\left(1 + \frac{c_p}{c}\right)^{-1},$$

$$\phi_2(t) = \frac{\dot{a}a^2}{cb} - \phi_1(t - t_*), \tag{8}$$

$$F(t) = -\frac{2(1-\nu)Pl}{E} - \frac{1-\nu}{1+\nu}\left(\frac{\phi(t)}{l} + \frac{\varphi(t)}{l^2}\right) + \frac{c_p^2}{c^2}\frac{\phi(t)}{l}.$$

Here, t_* is the solution of the equation $ct_* = l(t - t_*) - b(t)$. When $t_* = 0$, then $t = t_2$ (t_2 is the onset of the third period), and potentials ϕ_1, ϕ_2 and crack length are determined from the relationships

$$l(t_2) = b(t_2),$$

$$\phi_1(t_2) = \frac{1}{2}\left[F(t_2) + \frac{\dot{a}(t_2)a^2(t_2)}{cb(t_2)}\left(1 - \frac{c_p}{c}\right)\right], \tag{9}$$

$$\phi_2(t_2) = \frac{1}{2}\left[-F(t_2) + \frac{\dot{a}(t_2)a^2(t_2)}{cb(t_2)}\left(1 + \frac{c_p}{c}\right)\right].$$

The results of the second stage are used as initial data for the third.

Crack front movement velocity is determined according to [6] from the formula

$$\dot{l} = \begin{cases} 0 & \gamma \le \tilde{\gamma}_0, \\ \dfrac{V_{\max}}{c} \cdot \dfrac{1 - e^{1-\sqrt{\gamma/\tilde{\gamma}_0}}}{1 - e^{1-\sqrt{\tilde{\gamma}_1/\tilde{\gamma}_0}}} & \tilde{\gamma}_0 < \gamma < \tilde{\gamma}_1, \\ \dfrac{V_{\max}}{c} & \gamma \ge \tilde{\gamma}_1, \end{cases} \tag{10}$$

where $\tilde{\gamma}_0, \tilde{\gamma}_1$ are specific surface energy for crack formation at the start of a crack and the start of branching; γ is the current value of energy going into formation of a unit of crack surface.

Following [3] we find the value of γ

$$\gamma = \frac{(1-\nu)l}{2E}\sqrt{\frac{\pi}{N}}\,\sigma_\theta^2(l + 0). \tag{11}$$

It is assumed that in the crack zone the number of conical blocks N cut out is an additional parameter of the process determining the level of rock breaking. Calculation with prescribed N makes it possible to determine the maximum radius up to which the system of N radial cracks may propagate.

We consider the version, when $\sigma_r^c(b + 0) + \sigma_c > 0$, where σ_c is strength in uniaxial compression. In this case, the boundary of transition from crushing to fracturing is immobile during radial crack development (b = const).

DYNAMICS OF STEMMING EJECTION AND GAS OUTFLOW FROM THE EXPLOSION CAVITY

Movement of stemming in a cylindrical borehole under the action of detonation product pressure is considered in a one-dimensional statement. We designate the coordinate of the start of stemming as a_z, and its length as d_z (Fig. 1). In the initial instant of time the ends of the stemming and borehole do not coincide ($d_z \le l_z$). We suppose that stemming density ahead of the shock wave front is ρ_0, and at the front material is compacted step-wise to the value ρ_1 subsequently remaining incompressible.

The equation for movement of the compacted part of the stemming has the form [1]

$$\rho_1 \ddot{a}_z = k\sigma_z + \frac{\partial \sigma_z}{\partial z}, \qquad k = 2\mu\zeta / a_{00}, \tag{12}$$

where σ_z is stress tensor component, μ is material friction coefficient over the borehole wall, ζ is the ratio of the radial and longitudinal stress tensor components. By integrating this expression with respect to z we obtain

$$\sigma_z = \frac{\rho_1}{k}\ddot{a}_z + A(t)e^{-kz}. \tag{13}$$

At the contact boundary of the stemming with detonation products a condition of stress and pressure equality is fulfilled

$$\sigma_z\Big|_{z=a_z} = -p(\hat{\rho}). \tag{14}$$

Taking account of (14) expression (13) is rewritten as:

$$\sigma_z = \frac{\rho_1}{k}\ddot{a}_z - (p + \frac{\rho_1}{k}\ddot{a}_z)\, e^{-k(z-a_z)}. \tag{15}$$

We partition stemming movement into five stages.

First Stage. Immediately after the explosion cavity is filled with gases a packing shock wave starts to propagate through the stemming. We designate the current coordinate of its front in terms of $b_z(t)$. At the front with $z = b_z$ the law of mass conservation should be fulfilled $\rho_0 b_z = \rho_1 (b_z - \dot{a}_z)$, whence it follows that $b_z = \dot{a}_z / \theta$, $\theta = (\rho_1 - \rho_0)/\rho_1$.

Using the initial conditions $a_z\Big|_{t=0} = a_0$, $b_z\Big|_{t=0} = a_0$, we obtain

$$b_z = \frac{a_z - a_0}{\theta} + a_0. \tag{16}$$

We determine the stress at the shock-wave front

$$\sigma_z\Big|_{z=b_z} = -\rho_0 \dot{a}_z \dot{b}_z = -\rho_0 \dot{a}_z^2 / \theta. \tag{17}$$

From boundary condition (17) and formulas (15) and (16) there follows an equation for movement of the compacted part of the stemming

$$\ddot{a}_z = \frac{(pe^{-k(a_z-a_0)/\theta_0} - \rho_0 \dot{a}_z^2/\theta)k}{\rho_1(1 - e^{-k(a_z-a_0)/\theta_0})}, \qquad \theta_0 = \frac{\rho_1 - \rho_0}{\rho_0}. \tag{18}$$

This stage ceases when the packing wave front reaches the end of the stemming ($b_z = d_z + a_0$) and the next stage commences.

Second Stage. The stemming flies as a solid entity until its end reaches the end of the borehole $(a_z = d_z(\theta - 1) + a_0 + l_z)$. The movement equation has the form

$$\ddot{a}_z = \frac{pe^{-kd_z(1-\theta)}k}{\rho_1(1-e^{-kd_z(1-\theta)})}. \tag{19}$$

Third Stage. The stemming flies as a solid entity until its end emerges from the borehole to a value equal to $2a_{00}$, $a_z \le d_z(\theta-1) + a_0 + l_z + 2a_{00}$ or the start of the stemming is up to the edge of the borehole $(a_z = a_0 + l_z)$. Within the following condition is fulfilled

$$\sigma_z\Big|_{z=a_0+l_z} = -(a_z + d_z(1-\theta) - a_0 - l_z)\rho_1\ddot{a}_z. \tag{20}$$

A movement equation follows from (15) and (20)

$$\ddot{a}_z = \frac{pe^{-k(l_z - a_z + a_0)}}{\rho_1[a_z + d_z(1-\theta) - l_z - a_0 + (1-e^{-k(l_z - a_z + a_0)})/k]}. \tag{21}$$

The Fourth Stage commences when the ejecting end of the stemming starts to scatter. It is assumed that this occurs if $a_z \ge d_z(\theta-1) + a_0 + l_z + 2a_{00}$. The following condition should be fulfilled at the edge of the borehole

$$\sigma_z\Big|_{z=a_0+l_z} = -2a_{00}\rho_1\ddot{a}_z. \tag{22}$$

It follows from (15) and (22) that movement in the fourth stage:

$$\ddot{a}_z = \frac{pe^{-k(l_z + a_0 - a_z)}}{\rho_1[2a_{00} + (1-e^{-k(l_z + a_0 - a_z)})/k]}, \tag{23}$$

and it cannot exist if $d_z(1-\theta) \le 2a_{00}$.

Fifth Stage. When the start of the stemming reaches the borehole opening outflow of gases from the explosion cavity commences. This process is described by means of the Bernoulli law for a cylindrical charge [7]. Gas density within the borehole is determined as $\hat{\rho} = M/W$. Taking account of the fact that $W = 4\pi a^3/3 + \pi a_{00}^2(a_z - a)$ we have

$$\frac{\hat{\rho}}{\hat{\rho}_0} = m\left(\frac{a^3}{a_0^3} + \frac{3}{4}\left(\frac{a_{00}}{a_0}\right)^2\left(\frac{a_z - a}{a_0}\right)\right)^{-1}, \quad m = \frac{M}{m_0}, \quad m_0 = \frac{4}{3}\pi\hat{\rho}_0 a_0^3, \tag{24}$$

where m_0 is the weight of gas in the cavity at the initial instant. Knowing the critical velocity and density of the gas at the outlet from the borehole $\hat{V}_1$, $\hat{\rho}_1$ (formulas (31) in [7]) the value of *m* is found from the equation

$$\frac{dm}{dt} = -\frac{3\hat{V}_1\hat{\rho}_1 a_{00}^2}{4\hat{\rho}_0 a_0^3}. \tag{25}$$

PENETRATION OF DETONATION PRODUCT GASES INTO FAILED MEDIUM

The requirement of considering penetration of gases into the medium during an explosion was first substantiated by experimental laboratory explosions in sand [8]. In monolithic rocks within the zone of intensive shear crushing close to the charge conditions are similar to those in sand for the leakage of gases from the explosion cavity and penetration of them into a radial crack systems. For an elastically deformable porous medium without failure the question of gas filtration during an explosion was considered in [9]. In the present work the effect of penetration of detonation gases into the blasted medium that takes place at the instant of the origination of a radial crack zone is evaluated. It was assumed that gas enters the cracks formed instantaneously and its pressure due to intensive heat exchange with the medium changes according to an isotherm [9]. Calculations of this stage of an explosion and the developing crack system were carried out in a quasi-static approximation. Deformation of two zones was examined: radial crack $(b < r < l)$ and elastic $(r > l)$ zones.

At the boundary of the crushing zone $r = b$ as a result of the second stage of the explosion radial displacement forms $u_b = u(b, t_2)$, that subsequently may remain constant due to the effect of material packing in the crushing zone with compression of the cavity or it may increase under the action of gas pressure. In the last case at the intervnl boundary of the crack zone a radial stress is prescribed $\sigma_r(b, t) = -p(\hat{\rho})$. Crack sides are loaded by gas pressure p, and at infinity in the elastic zone rock pressure P acts. The solution of the problem for equilibrium of these zones in a static statement with indices p, P, u_b, b and l makes it possible to find the stresses and strains in the vicinity of the crack front, and to determine the surface energy γ going into radial crack development. The problem is simplified if the stress state of compression created by uniform pressure p is subtracted from the solution sought. Then crack edges become free and at infinity in the elastic zone pressure $P - p$ acts. At the internal boundary of the radial crack zone displacement $u_b' = u_b + b(1-2\nu)(p-P)/E$ is prescribed if $\sigma_r(b) < 0$ or $\sigma_r(b) = 0$. The solution of this problem using the energy condition at the radial crack front (11) makes it possible to determine γ:

$$\gamma = \frac{(1-\nu)l}{2E}\sqrt{\frac{\pi}{N}}\,(3(P-p)-q_l)^2, \tag{26}$$

$$q_l = \sigma_r(l) = -\frac{\dfrac{u_b'}{b} + \dfrac{3(1-\nu)l}{2bE}(P-p)}{1-\dfrac{(1-\nu)b}{2l}} \cdot \frac{b^2}{l^2}, \quad \text{if} \quad \sigma_r(l) < 0, \quad \text{otherwise} \quad q_l = 0.$$

For p from the condition for isothermal expansion we have $p/\hat{\rho} = p_* V_0$, where $p_* = 10^5$ Pa, V_0 is specific gas release during the explosion. Gas density $\hat{\rho}$ may be determined knowing the volume occupied by it. If it is assumed that in the region $r < l$ the medium is unloaded, then the volume of gas is defined by expansion of the crack front surface under the action of external tension $(P - p)$ and the expanding action of the crushing zone

$$W = 4/3\pi a^3 + \pi a_{00}^2(a_z - a) + \Delta W,$$

where

$$\Delta W = 4\pi l^3 \left(\frac{1+\nu}{2E}(p - P - q_l) - \frac{1-2\nu}{E} P \right) + \frac{4\pi p(1-2\nu)(l^3 - a_0^3)}{E}.$$

Solution of the equation $p = p_* V_0 M / W$ with respect to p makes it possible to determine q_l and γ. Knowing γ, it is possible to find $\dot{l}$ from (26) and to calculate the dynamics of the radial crack system.

Consideration of stemming movement during gas penetration was carried out by Eqs. (18), (19), (21), and (23) within which pressure p was determined as described above according to an isotherm. In order to calculate the outflow of gases from the borehole after ejection of the stemming relationship (25) was used where the critical values of velocity $\hat{V}_1$ and gas density $\hat{\rho}_1$ were found from the condition for adiabatic outflow of gas with parameters p and $\hat{\rho}$, determined from the isotherm. In this stage explosion cavity expansion is large and the index of the adiabat is γ_2. Critical parameters are found from [7]

$$\hat{\rho}_1 = \hat{\rho} \left(\frac{2}{1+\gamma_2} \right)^{\frac{1}{\gamma_2 - 1}}, \qquad \hat{V}_1 = \sqrt{\frac{2\gamma_2 V_0 p_*}{1+\gamma_2}}.$$

NUMERICAL SOLUTION

Solution of the problem of stemming ejection and crack propagation was obtained by integrating a set of ordinary differential equations of the first order by the Euler method.

Calculations were performed with the following values of parameters taken as the basic set: $E = 5 \cdot 10^{10}$ Pa, $\rho = 2500$ kg/m^3, $\nu = 0.3$, $Y = 10^6$ Pa, $Y_2 = 10^8$ Pa, $P = 10^5$ Pa, $\alpha = 4$, $\alpha_2 = 9$, $p_0 = 3.32 \cdot 10^9$ Pa, $\tilde{\gamma}_0 = 40$ J/m^2, $\tilde{\gamma}_1 = 120$ J/m^2, $a_0 = r_0 = 0.05$ m, $V_{\max} = 850$ m/s, $N = 8$, $\rho_0 = 1500$ kg/m^3, $\rho_1 = 2000$ kg/m^3, $\hat{\rho}_0 = 1000$ kg/m^3, $\varsigma = 0.5$, $\mu = 0.5$. Here, α_2 and Y_2 are indices of the strength condition for shear failure of elastic medium taken in the form of the Coulomb – Mohr rule [2]. The following were adopted as units of measurement in the calculations: r_0 for length, c for velocity, ρ for density, r_0 / c for time, and E for stress.

Curves are presented in Figs. 2 and 3 for the dependence of the weight of gas in the explosion cavity and radial crack lengths on time obtained with different values of stemming length d_z and the rest of the parameters taken from the basic set. Gas release V_0 was taken as 0.5 m^3/kg (data for trotyl). Curves in Figs. 2*b* and 3*b* are calculated with gas penetration into cracks, and those in Figs. 2*a* and 3*a* are calculated without it. The upper curves in Figs. 2*a* and 3*a* correspond to calculation of a confined explosion without a borehole with stemming, and the rest are with a borehole, when $l_z = 20$ and $a_{00} = 1$. It can be seen by comparing the curves in Fig. 2*a*, *b* that gas penetration into crushed medium markedly increases (by a factor of 3 – 6) the maximum size of the crack zone. The time for the development of breaking increases by an order of magnitude. This situation leads to the fact that under gas penetration conditions the periods for gas outflow after ejection of the stemming and breaking are comparable, and without penetration crack stopping occurs much more rapidly and therefore the requirement for stemming in this version (Figs. 2*a*, 3*a*) is much lower. It can be seen in Fig. 2*a* that starting with $d_z \geq 2.5$, the reduction in the size of the crack zone is not more than 10% compared with explosion without a borehole: with gas penetration (Fig. 2*b*) these changes follow when $d_z \geq 7.5$.

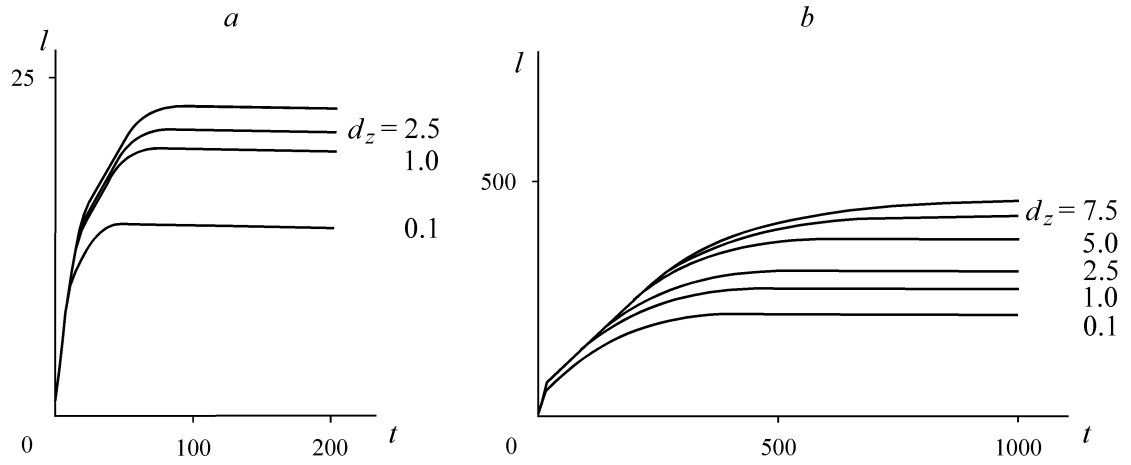

Fig. 2

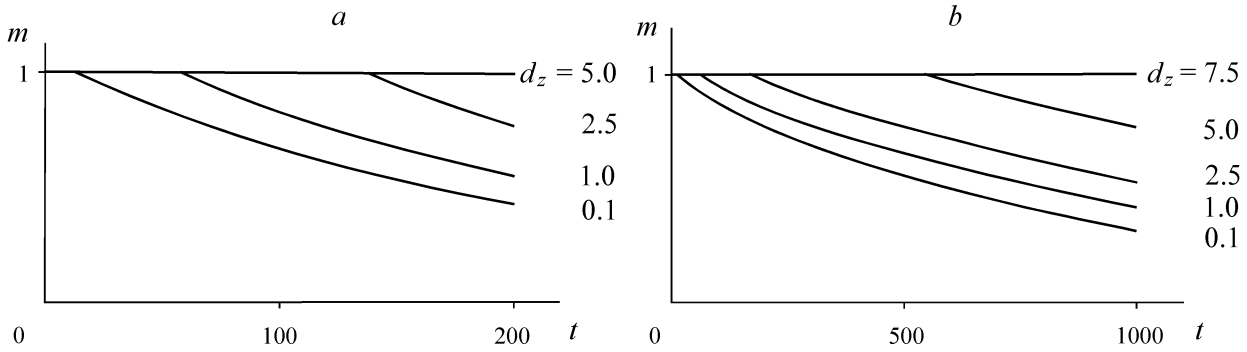

Fig. 3

Breaks in the curves in Fig. 3 correspond to the start of gas outflow from the borehole as a result of which there is a drop in pressure in the cavity. If this occurs sooner than the maximum l is reached during explosion of a confined charge calculated without a borehole with stemming, then there is also a substantial reduction in the maximum dimensions of the crack zone.

Curves are presented in Fig. 4 for the dependences of maximum radial crack zone dimensions l_* on the initial charge radius a_0 in the case of a confined explosion without a borehole with stemming (all of the parameters were taken from the basic set). Curve *1* corresponds to solution of the problem without gas penetration into broken medium taking account of dynamics in the crack and elasticity zones; curve *2* corresponds to quasi-static consideration of the dynamics of the elastic zone and radial crack zone without gas penetration into the medium; curve *3* is calculated by the quasi-static model with isothermal entry of gases into cracks. It can be seen from the curves that gas penetration increases the dimensions of the breaking zone by a factor of four. Comparison of curves *1* and *2* shows that the error in calculation by the quasi-static model compared with the dynamic model is quite small and it increases from 8 to 16% with an increase in a_0 from 1 to 4. The increase in relative crack dimensions due to the scale of the explosion is explained by the fact that with brittle failure geometric similarity is violated.

Curves are shown in Fig. 5 for the dependence of maximum crack zone dimensions on stemming length calculated with different values of friction coefficient k with two values of the initial radius a_0 and $l_z = 20$. It can be seen that a reduction in friction essentially weakens the effect of stemming in the case of small charges, but with an increase in the initial charge radius the requirements for it lessen.

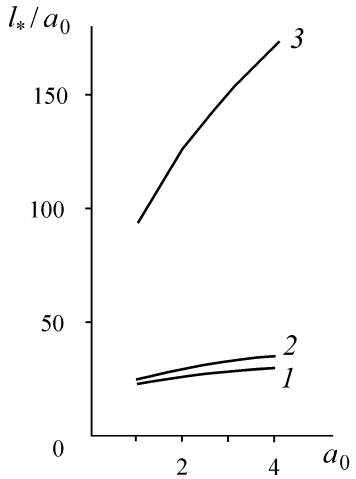

Fig. 4

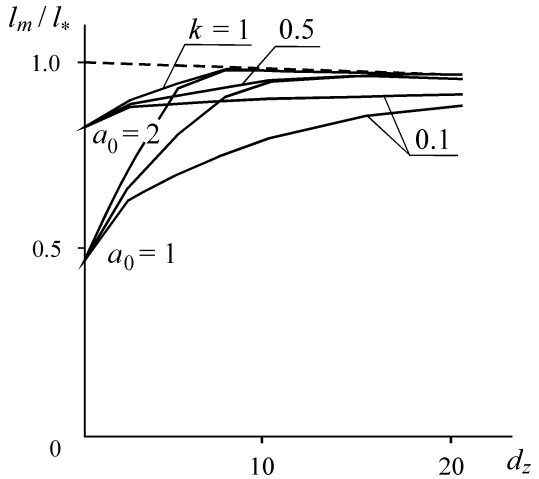

Fig. 5

CONCLUSIONS

Gas penetration into broken medium substantially increases (by a factor of 3 to 6) radial crack zone dimensions.

Outflow of gases from a borehole with stemming leads to a reduction in crack dimensions. Introduction of stemming with a length of $2.5a_0$ without entry of gases into the medium provides 90% breaking compared with an explosion without a borehole, and with penetration of them the required stemming length increases to $7.5a_0$. The time delay, when equilibrium is established between gas pressure in broken medium due to filtration, may increase markedly the role of gas outflow into the atmosphere.

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