EMISSION OF ELASTIC WAVES IN AN EXPLOSION IN A POROUS ELASTIC–PLASTIC MEDIUM

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Seismic waves generated in an underground explosion were calculated in [1-4] by making certain simplifying assumptions. In [1, 2] the medium behind the shock front was assumed incompressible. The basic parameters of longitudinal elastic waves emitted in an explosion were estimated in [3] by an approximate scheme of evolution of an explosion in solid rock. Koryavov [4] treated the effect of the elastic precursor on motion in the near zone of an explosion for solid rock under the assumption that at the wave front the shear fracture condition is satisfied, and behind the shock front the medium has no strength, and is described by an equation of state derived from the shock adiabat for the solid. It is of interest to treat the problem of the emission of an elastic wave with minimum simplifying assumptions, the equations for which can only be solved numerically (e.g. [5, 6]). One of the important problems in the study of the seismic effect of an underground explosion in actual soils and rocks is that of deriving the detailed characteristics of the elastic waves emitted. Here it is necessary to take account of factors which affect the formation of the elastic signal: the presence of porosity of the medium, the character of the saturation of the pores, the inhomogeneity of the deformation of the actual medium. Rodean [7] took account of these factors by empirical relations. On the other hand, the physical picture of the emission of elastic waves in an underground explosion must from the very beginning take account of the dynamics of the formation of the elastic signal in media with complex rheology. In the present article we investigate the emission of elastic waves in an underground explosion, taking account of the dynamics of the deformation of a porous saturated medium (variable compressibility of the medium at the front of the loading wave, unloading behind the front, the irreversible character of the volume strains). The investigation was performed by using the numerical solution of the system of hydrodynamics equations which take account of the shear strength of the medium. A model equation of state takes account of the fact that the medium consists of several components. The profile of the elastic precursor is refined by recalculation. We analyze the effect of porosity, the strength parameters of the medium, and the nature of the saturation on the characteristics of the elastic wave emitted.

The source of the explosion is modeled by an expanding cavity filled with an adiabatic gas. In Lagrangian coordinates the system of equations describing the motion of the medium has the form

$$\frac{\partial v}{\partial t} = v_0 \frac{r^2}{r_0^2} \frac{\partial u}{\partial r_0} + \frac{2vu}{r}, \quad \frac{\partial u}{\partial t} = v_0 \frac{r^2}{r_0^2} \frac{\partial \sigma_r}{\partial r_0} + \frac{2v\tau}{r}, \tag{1}$$

$$\frac{\partial e}{\partial t} = -p\frac{\partial v}{\partial t} + \frac{2}{3}\tau\left(v_0 \frac{r^2}{r_0^2}\frac{\partial u}{\partial r_0} - \frac{vu}{r}\right), \quad r = r_0 + \int_0^t u\,dt,$$

where v and e are the specific volume and specific energy of the multicomponent medium; v_0, initial specific volume; u, velocity; $\tau = \sigma_r - \sigma_\varphi$; $p = -(\sigma_r + 2\sigma_\varphi)/3$; σ_r and σ_φ, radial and angular components of the stress tensor; r and r_0, Eulerian and Lagrangian coordinates; and t, time. The system of equations (1) is closed by the equation of state of the medium and the elastic–plastic relations: in the elastic region, Hooke's law

$$\partial\tau/\partial t = 2G(\partial u/\partial r - u/r), \tag{2}$$

where G is the shear modulus;
in the plastic region

$$|\tau| = \alpha + kp, \tag{3}$$

where α is the coefficient of cohesion and k is the coefficient of friction.

The stress tensor σ_{ij} is related to the stress tensor σ_{ij}^0 in the solid component and the pressure q of

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the gas (or liquid) in the pore [8]:

$$\sigma_{ij} = (1 - m)\sigma_{ij}^0 - mq\delta_{ij},$$

where m is the volumetric porosity and δ_{ij} is the Kronecker symbol. The pressure in the solid component was related to that in the material saturating the pore by using a model of a multicomponent medium [9] which satisfactorily describes the behavior of porous gas-saturated and water-saturated soils and rocks during loading and unloading. Macroscopic plastic flow and plastic flow in the vicinity of a pore are described by different strength parameters. It is assumed that a pore is much smaller than the fragments into which the medium is disintegrated. This model of a medium is described in [10].

The system of equations (1)-(3) was integrated numerically. An artificial linear-quadratic viscosity [10] was introduced to smear out the discontinuities. The elastic wave emitted was recalculated by the following scheme. The hodograph of the point separating the elastic and plastic regions at the front of the loading wave $R_*(t)$ was calculated, and then the values of the radial stresses at $R_*(t)$ were computed. The parameters of the elastic wave can be expressed in terms of a single unknown function $f(\xi)$ – the potential of elastic displacements:

$$v^* = c_0\left[\frac{\ddot{f}(\xi)}{x} + \frac{\dot{f}(\xi)}{x^2}\right], \sigma_r^* = -\rho_0 c_0^2\left[\frac{\ddot{f}(\xi)}{x} + 2\frac{1-2\nu}{1-\nu}\left(\frac{\dot{f}(\xi)}{x^2} + \frac{f(\xi)}{x^3}\right)\right] - p_*,$$

$$\sigma_\varphi^* = -\rho_0 c_0^2\left[\frac{\nu}{1-\nu}\frac{\ddot{f}(\xi)}{x} - \frac{1-2\nu}{1-\nu}\left(\frac{\dot{f}(\xi)}{x^2} + \frac{f(\xi)}{x^3}\right)\right] - p_*, \rho^* = \rho_0\left[1 - \frac{\ddot{f}(\xi)}{x}\right],$$

where $\xi = c_0t/a - x$; $x = r/a$; v^*, velocity; ν, Poisson's ratio; p_*, lithostatic pressure; a, radius from which the emission of elastic waves begins; and c_0, longitudinal sound speed. In order to find $f(\xi)$ it is sufficient to solve the equation specified on the line $r = R_*(t)$:

$$\left[\frac{\ddot{f}(\xi)}{x} + 2\frac{1-2\nu}{1-\nu}\left(\frac{\dot{f}(\xi)}{x^2} + \frac{f(\xi)}{x^3}\right)\right]_{x=R_*(t)/a} = -\frac{\sigma_r(r = R_*(t))}{\rho_0 c_0^2}.$$

This ordinary differential equation was integrated numerically by the Runge–Kutta method with zero initial conditions $f(0) = 0$, $\dot{f}(0) = 0$. The elastic energy radiated in the explosion was calculated from the formula

$$e^* = 4\pi\rho_0 a^3 c_0^2 \int_0^\infty [\ddot{f}(\xi)]^2 d\xi.$$

Calculations show that the introduction of an artificial viscosity leads to the flattening out of the profile of the elastic precursor. Figure 1 compares the profiles of the radial stress in the loading wave with recalculation of the elastic energy (solid curve) and without recalculation [10] (open curve) at a distance $7a$ for a porosity of 7%. The calculated results show that most of the radiated elastic energy is emitted during the motion of the plastic loading wave front (i.e., up to the instant the plastic region at the front of the loading wave disappears). This effect is related to the fact that the rate of radiation of elastic energy is proportional to the product of the radial stress and the mass velocity in the elastic wave, and at this stage of the radiation the stress level and the mass velocity at the elastic precursor being separated are very appreciable.

With an increase in gas-saturated porosity the amplitude of the loading wave is more strongly damped, the plasticity radius is decreased, and accordingly the time of radiation of elastic energy is decreased. For increased porosity the amplitude of the elastic wave at separation (at the point $R_*(t)$) decreases more rapidly with time. Therefore, an increase in gas-saturated porosity leads to a considerable decrease of the elastic energy radiated (in Fig. 2 ε is the ratio of the elastic energy radiated to the total energy of the explosion). The apparent frequency (at which the maximum of the radiated elastic energy occurs) increases with increasing porosity. For example, for an increase in gas-saturated porosity from 3 to 13% the apparent frequency is

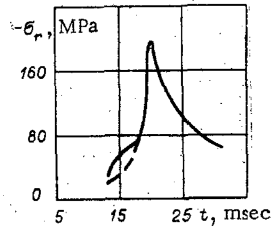

Fig. 1

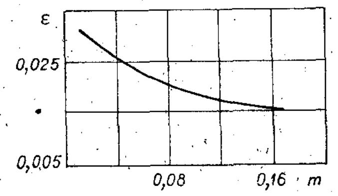

Fig. 2

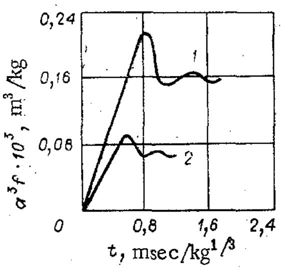

Fig. 3

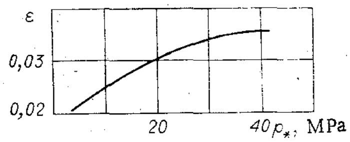

Fig. 4

increased by 30%. The remanent displacements in the elastic range, which are proportional to $f(\infty)/r^2$, are approximately halved. Figure 3 shows the time dependence of the elastic displacement potentials for gas-saturated porous media (1, m = 3%; 2, m = 13%).

The elastic energy radiated relative to the total energy of the explosion is plotted in Fig. 4 as a function of the lithostatic pressure. The porosity decreases with increasing lithostatic pressure. This leads to an increase of the seismic energy radiated which agrees with experiment [11].

The saturation of pores by a liquid makes the medium more rigid than a gas-saturated medium, and increases the plasticity radius and the time of radiation of elastic energy. This leads to an increase in the elastic energy radiated, and a decrease in the apparent frequency.

Calculations show that a variation of the strength parameters of the medium has little effect on the elastic energy radiated. Thus, for an increase in the coefficient of cohesion from 15 to 30 MPa at constant porosity, the elastic energy radiated is decreased by 5%. An increase in the coefficient of cohesion of the medium leads to a decrease in the time of emission of the elastic wave, and an increase in the stress level in the separated elastic precursor.

Thus, gas-saturated porosity is the main factor affecting the evolution of an underground explosion. An appreciable stress concentration in the vicinity of pores leads to plastic flow and filling of the pores. This has a substantial effect on the nature of the propagation of the plastic loading wave, and also on the elastic wave which is formed at the plastic wave front.

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