DISSIPATION OF THE ENERGY OF AN EXPLOSION IN A POROUS ELASTOPLASTIC MEDIUM

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A considerable fraction of the energy of an explosion in a solid medium is dissipated in the substance surrounding the charge. The dissipation of the energy of an explosion takes place behind the front of a shock wave with plastic flow of the substance behind the front of the shock wave. Part of the energy goes over into the energy of the residual elastic deformations. A small part of the total energy of the explosion is emitted in the form of shock waves. Many real rocks are porous, with one degree or another of gas or water saturability. Therefore, the question of energy losses with an explosion in porous saturated media is of considerable interest [1]. A theoretical study of the question of the dissipation of the energy with an explosion in a porous medium, whose deformation takes place plastically, was made in [2, 3]. The consideration given in these communications is limited to the case of the complete collapse of the empty pores at the shock front. The substance behind the front of the shock wave was assumed to be incompressible. In the present article an investigation is made of the redistribution of the energy of an underground explosion in a saturated porous medium. The investigation was made using a numerical solution of a system of equations of hydrodynamics, taking account of the shear strength of the porous substance. The discussion is limited by the assumption of the equality of the pressures in the skeleton and the saturated gas or liquid. Multicomponent media are taken into consideration using a model equation of state.

1. The starting system of equations describing an underground explosion under the assumption of spherical symmetry, written in Lagrangian variables, has the form

$$\frac{\partial v}{\partial t} = v\left(\frac{\partial u}{\partial r} + 2\frac{u}{r}\right),$$
$$\frac{\partial u}{\partial t} = v\left(\frac{\partial \sigma_r}{\partial r} + 2\frac{\tau}{r}\right), \quad \frac{\partial e}{\partial t} + p\frac{\partial v}{\partial t} = \frac{2}{3}v\left(\frac{\partial u}{\partial r} - \frac{u}{r}\right)\tau, \tag{1.1}$$

where v and e are the specific volume and the specific energy of the medium as a whole; u is the velocoty; $\tau = \sigma_r - \sigma_\varphi$; σ_r and σ_φ are the radial and tangential components of the stress tensor; $p = -1/3(\sigma_r + 2\sigma_\varphi)$ is the pressure e. The Euler coordinate r is connected with the Lagrangian coordination r_0 by the relationship

$$r = r_0 + \int_0^t u(r_0; t')\,dt'.$$

The tensor σ_{ij} is the total tensor of the stresses, acting on an element of the porous medium. In turn, σ_{ij} can be connected with the stresses $\sigma_{ij}^{(1)}$, acting in the solid component, and with the pressure of the gas or liquid p_1, filling the pores [4]:

$$\sigma_{ij} = (1 - m)\sigma_{ij}^{(1)} - mp_1\delta_{ij}$$

(m is the porosity; δ_{ij} is the Kronecker symbol).

The further assumption is made that the pressures in the skeleton and the substance in the pores are equal, i.e., we shall assume that $\delta_{ii}^{(1)} = -3p_1$. Such a postulation is completely justified in the region of high pressures (≥10 kbar). With small external loads, the pressures in the skeleton and the saturated pores will be different. In what follows, these dif-

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ferences are neglected. The study of the case $\sigma_{ii}^{(1)} = 3p_1$ is the subject of a separate investigation.

The flow of the porous substance is described by the following relations:

in the elastic region

$$\frac{\partial \tau}{\partial t} = 2G\left(\frac{\partial u}{\partial r} - \frac{u}{r}\right);$$

in the plastic region

$$|\tau| = \sigma^* + kp,$$

where G is the shear modulus; σ^* is the adhesion; k is the coefficient of dry friction.

The system of equations (1.1) is closed by the thermodynamic equation of state. For a multicomponent medium, we take the equation of state in the form [5, 6]

$$e = \sum_{i=1}^{3} R_i e_i, \quad v = \sum_{i=1}^{3} R_i v_i, \tag{1.2}$$

where e_i and v_i are the specific energies and volumes of the corresponding components; R_i are their weight contents $\left(\sum_{i=1}^{3} R_i = 1\right)$.

The equations of state for the solid component and the substance in the pores (gas or liquid) were taken in the Mie–Grüneisen form [7]

$$\begin{gathered} p = B_i\left[\left(\frac{v_{0i}}{v_i}\right)^{n_i} - 1\right] + \frac{\Gamma_i c_i (T - T_0)}{v_i}, \\ e_i = B_i v_{0i}\left\{\frac{1}{n_i - 1}\left[\left(\frac{v_{0i}}{v_i}\right)^{n_i - 1} - 1\right] - \left[1 - \frac{v_i}{v_{0i}}\right]\right\} + c_i (T - T_0). \end{gathered} \tag{1.3}$$

In carrying out the actual calculations, the constants entering into (1.3) were determined on the basis of data given in [8].

Water: $B_1 = 3.2 \cdot 10^3$ bar; $v_1^{-1} = 1$ g/cm^3; $n_1 = 7$; $\Gamma_1 = 0.6$; $T_0 = 273$°K; $c_1 = 3.72 \cdot 10^3$ kJ/T•deg.

Solid skeleton: $B_2 = 10^5$ bar; $v_2^{-1} = 2.65$ g/cm^3; $n_2 = 3$; $\Gamma_2 = 1$; $T_0 = 273$°K; $c_2 = 10^3$ kJ/T•deg; $G = 10^5$ bar.

The gaseous component was assumed to be an ideal gas with the adiabatic index $\varkappa = 1.4$. We note that the temperature of all the components was assumed to be identical. Corresponding evaluations are given in [9]. The system (1.1)-(1.3) was replaced by a system of equations in finite differences. The difference scheme, analogous to [10], had a second order of exactness with respect to the time and the coordinate, by virtue of the use of a uniform Lagrangian grid, which remained unchanged for the course of the whole calculating process. For the purpose of smoothing out the hydrodynamic discontinuities, an artificial linear–quadratic viscosity was introduced [10]. The stability of the scheme was assured by an appropriate selection of the time spacing Δt. The use of a pseudoviscosity offered the possibility of a straight-through numerical calculation from the center of the gas cavity to the unperturbed medium.

The explosion was modeled by an expansion of a gas cavity with a radius a_0 with an initial pressure of 400 kbar. The calculating points inside the cavity made it possible to take account of the complex gasdynamic motion of the gas inside the cavity, which was assumed to be ideal with an adiabatic index of 1, 2.

2. The energy characteristics of the medium with an underground explosion for different calculating variants are given in Table 1,

$$E_1 = 4\pi \int \rho \frac{u^2}{2} r^2 dr$$

is the kinetic energy of the medium (the integrals in E_1 and E_2 are taken over the air region);

$$E_2 = 4\pi \int dt \int \frac{2}{3} \tau \left(\frac{\partial u}{\partial r} - \frac{u}{r} \right) r^2 dr$$

is the energy dissipated due to plastic flow;

$$E_3 = \pi \int p_H (v - v_H) r^2 dr$$

is the energy dissipated in the wave front (p_H, v_H are the pressure and the volume at the shock front);

$$E_4 = 4\pi \int \left(\frac{\tau^2}{2G} + \frac{p^2}{2K} \right) r^2 dr$$

is the energy of the elastic deformations, including both shearing and volumetric reversible deformations (K is the modulus of volumetric compression of a multicomponent medium); E_5 is the energy of the gases inside the cavity. In Table 1, the upper numbers in each row denote the fraction of the corresponding energies with respect to the total energy of the explosion. The lower numbers show the fraction of the corresponding energy with respect to the energy given up to the surrounding cavity of the medium, i.e., to the total energy of the explosion, after the subtraction of the energies of the explosive gases inside the cavity. In what follows, the comparison will be made, unless specially stipulated, with respect to the lower numbers.

The data of Table 1 are given for the moment of time when the cavity has attained a maximal radius. However, since the reverse motion of the cavity for the selected strength parameters (see Table 1) is not great (less than 5% in all variants), the numbers, characterizing the distribution of the energies varies only slightly with a reverse motion of the cavity.

Carrying out the calculations by the above method, the strength parameters were varied: the adhesion σ^* and the coefficient of dry friction k, the starting porosity of the medium, and the character of the saturation of the pore space (gas or water).

Variants of the calculations 1-3 relate to the case of a monolithic medium. They show that the principal fraction of the energy is dissipated with plastic flow. With a rise in the strength parameters of the medium σ^* and k, this fraction rises. Thus, this mechanism of the dissipation of the energy of an explosion is dominating for the case of a medium with a zero porosity. We note that this result coincides with the conclusions of [2, 3].

A considerable part of the energy (10-20%) is dissipated due to shock compression. In addition, an appreciable part of the energy is found to be stored in the form of the elastic shear and compression energy. With a rise in the strength, the values of E_3 and E_4 decrease considerably. The decrease in E_3 is connected with a decrease in the region of the existence of shock-wave conditions; E_4 is connected with a decrease in the dimension of the region of large deformations, which takes place due to a decrease in the radius of the cavity with an increase in σ^* and k. It is important to note that the decrease in the kinetic energy of the medium E_1 with a rise in the strength parameters. Figure 1 shows the dependence of E_1/E_0 on the time, where E_0 is the total energy of the explosion (the numbering of the curves in all the figures coincides with the number of the variant in Table 1). It can be seen that with a rise in the strength parameters of the medium, it is more difficult to set the surrounding medium into motion with a gas explosion; as a result, the above-noted fall in the final value of E_1 takes place.

The variants of the calculations 5-7 relate to a dry gas-saturated medium with a different strength and porosity. From the data of Table 1, it can be seen that the principal dissipation of energy takes place with plastic flow and due to compression at the shock front. For weakly adhering media (k = 0, $\sigma^* = 150$ bar) (variant 5) the latter means of dissociation predominates. With a rise in the strength, the plastic dissipation increases and can exceed the dissipation at the shock front (variant 6). However, for media with moderate and high porosity (variant 7), the dissipation behind the shock front will always be the principal fraction. Calculations also show that the fraction of the elastic energy E_4 is lowered considerably with a rise in the porosity, and less sharply with a rise in the pore strength.

TABLE 1

Variant	Type of medium	σ^*, bar	K	Initial porosity, %	E_1	E_2	E_3	E_4	E_5
1	Medium with zero porosity	150	—	—	0,061 0,094	0,280 0,432	0,133 0,205	0,165 0,254	0,351
2	»	300	—	—	0,056 0,092	0,318 0,525	0,102 0,168	0,130 0,214	0,394
3	»	150	0,5	—	0,030 0,056	0,370 0,695	0,070 0,130	0,062 0,117	0,468
4	Water-saturated medium	150	—	12,5	0,030 0,046	0,282 0,432	0,230 0,353	0,122 0,187	0,348
5	Gas-saturated medium	150	—	2,67	0,0092 0,0141	0,254 0,390	0,356 0,539	0,037 0,057	0,351
6	»	300	—	2,67	0,0090 0,014	0,328 0,528	0,266 0,430	0,036 0,061	0,382
7	»	150	—	6,00	0,0084 0,0130	0,180 0,281	0,458 0,707	0,025 0,039	0,352

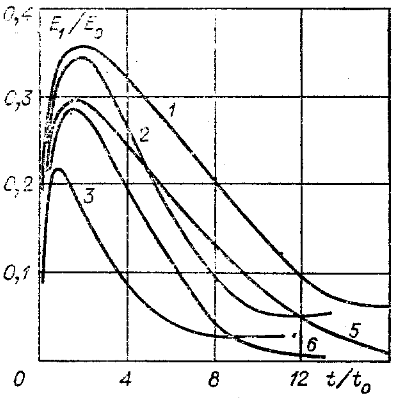

Fig. 1

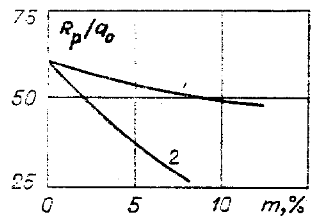

Fig. 2

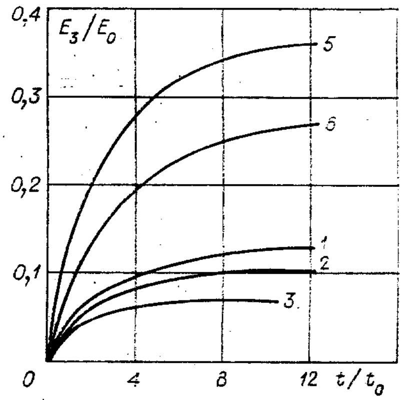

Fig. 3

This obviously takes place due to the fact that the zone of large shear stresses decreases with a rise in the porosity. This can be seen in Fig. 2, which illustrates the dependence of the maximal radius of the zone of plastic deformations R_p on the porosity of the medium with an unchanged power of the explosion (curve 1 corresponds to the case of a water-saturated medium, curve 2 to the case of a gas-saturated medium). The conclusion with respect to a considerable rise in E_3 with a rise in the porosity is confirmed by the results of experimental investigations [11]. The final value of the kinetic energy E_1 in a gas-saturated medium is approximately an order of magnitude less than the corresponding kinetic energy in a medium with zero porosity. This fact is important when considering elastic or seismic characteristics of the explosion.

For a water-saturated porous medium, the same tendencies are characteristic as for a dry porous medium; however, they have a weakly expressed character. Here, the energy distribution, in its parameters, approaches the energy distribution of an explosion in a nonporous medium. Therefore, with the saturation of the previously dry porous medium with water there will be a reinforcement of the mechanical effect of the explosion.

The results given in Fig. 3 show that the most intense process of dissipation at the shock front takes place in the initial stage of the development of the explosion. Then, the rise in the curves is smooth and, in the final stage, attains a constant value. Plastic dissipation (Fig. 4) is characterized by the fact that, with an increase in the effect of the strength parameters, the curves of $E_2(t)$ become more convex. The arrival of the curves at the asymptotic is connected with the end of the phase of plastic flow.

The dependence of the temperature of the medium on the radius at the moment of the stopping of the cavity is shown in Fig. 5. It can be seen that the temperature falls sharply with an increase in the distance from the wall of the cavity. There is appreciable heating-up of the medium only in a narrow region immediately adjacent to the cavity. This result is in

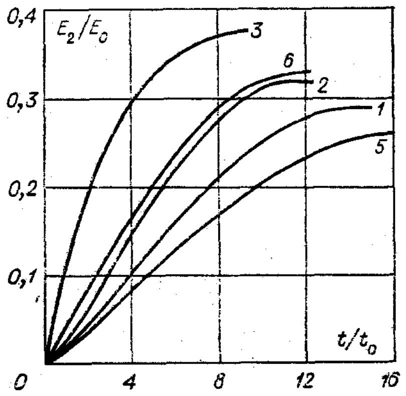

Fig. 4

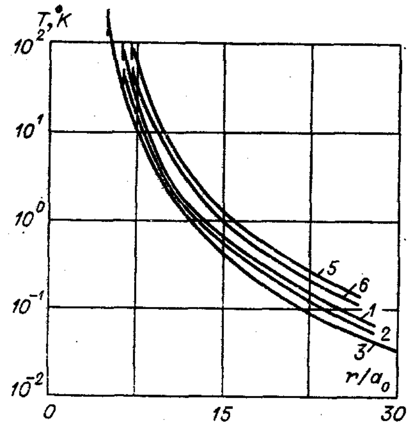

Fig. 5

agreement with the conclusions of [12]. The results given in Fig. 5 show that, with a rise in the porosity in a gas-saturated medium, the temperature of the medium increases due to the stronger heating-up, taking place behind the shock front.

In conclusion, we note the following. For a medium with a zero porosity, the principal dissipation of energy is connected with plastic flow. A considerable fraction of the energy is found to be stored in the elastic energy of the shear and compression deformation, which is reversible, and which can obviously be the source of secondary shock waves during the moments of time following the explosion. With a rise in the strength, this energy decreases; there is also a decrease in the value of the kinetic energy of the medium, which, during the last stages of the development of the explosion, can be associated with the energy radiated in the elastic stage.

For dry porous media, the principal mechanism of the dissipation of energy, connected with shock compression, i.e., with the irreversible heating of the medium at the front of the shock wave. The kinetic energy is an order of magnitude less than in a monolith, and decreases with a rise in the strength. The elastic energy is also less than that connected with a decrease in the zone of large deformations.

The saturation of dry media by water approaches the energy characteristics of the explosion to an explosion in a nonporous medium, i.e., to a reinforcement of the mechanical effect of the explosion.

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