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Methods of Control of Explosion Energy Distribution in Rocks

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Influence of the pulse shape on the formation of the stress field and the mechanism of rock destruction by rupture

The model of the action of an explosion on a medium discussed in Section 3 makes it possible to judge the quality of crushing only by the final results and does not allow one to study the processes occurring in the medium over time, since from the accepted assumptions about the incompressibility and instantaneous transfer of charge energy in the medium it follows that the energy spreads instantly.

In fact, when a charge explodes, the resulting gases under enormous pressure act on the walls of the charging chamber for a certain period of time, which is determined by the time of movement of the ram and the time of expiration of the detonation products from the charge cavity [58, 136]. Since the detonation process is short-term, as a result of the impact action of the detonation products, energy is transferred to the destroyed medium in the form of a wave impulse, under the influence of which the medium is deformed and destroyed. The parameters of this stress wave are predetermined by the shape of the initial impulse and the physical and mechanical properties of the rocks. Thus, by changing the shape of the initial pulse, it seems possible to influence the parameters of the stress wave, which play a certain role in the process of rock destruction, and therefore the final results of the explosion.

A fairly detailed study of the formation and propagation of stress waves during a charge explosion is available only in the case when pressure is instantly applied to the walls of the charging chamber, which subsequently remains constant:

$$P(t) = \begin{cases} 0, t \leq 0; \\ P, t > 0, \end{cases} \quad (1.1)$$

where P_0 - pressure of detonation products on the walls of the cavity.

However, as studies have shown, pressure reaches its maximum values after a certain period of time, and then it declines. At the present stage of development of blasting operations, it seems possible to manipulate the shape of the applied blast load, which significantly affects the formation of the stress field that predetermines the process of destruction of solid media by explosion. In this regard, there is an urgent need to study the influence of the shape of the explosive pulse on the formation of the stress field and the mechanism of rock destruction.

When studying the formation and propagation of stress waves from the explosion of a spherical charge in an elastic medium, we will assume that the pressure in the charge cavity changes over time according to the law:

(1.2)

$$P(t)=\begin{cases}0, & t\le 0;\\ \dfrac{P_o t}{t\max}, & 0\le t\le t\max;\\ P_0 e^{-\delta(t-tmax)}, & t>t\max,\end{cases}$$

where *S is* the pressure decay rate in the charge cavity, 1/sec;

tmax _ - time of pressure rise to maximum value;

t - current time.

To find radial and tangential stresses, displacements and displacement speeds for each point of the medium at any time, we will compose a dynamic equation for the elastic element of the medium.

(1.3)

$$\frac{\partial\sigma_r}{\partial r}+\frac{2(\sigma_r-\sigma_\theta)}{r}=-\rho\frac{\partial^2 U_r}{(\partial t)^2},$$

Where $\sigma_r\,\sigma_Q$ - radial and tangential stress, respectively;

U_r - displacements in the radial direction ;

r - distance from the center of the charge to the point under study.

Let's find the general solution to the equation :

(1.4)

$$\theta=\frac{\partial(r^2Ur\ )}{r^2\partial r},$$

We get (1.5)

$$\sigma_r=(\lambda+2\mu)\theta+\frac{4\mu}{r}U_r,$$

$$\sigma_\theta=\lambda\theta+2\mu\frac{U_r}{r}.$$

Equation (4.3) taking into account (1.4) - (1.6) is transformed to the form:

(1.6)

$$\frac{\partial^2(r\theta)}{\partial r^2}=\frac{1}{C^2}\frac{\partial^2(r-\theta)}{\partial t^2}.$$

Therefore, the solution to equation (1.7) must be sought in the form

(1.7)

$$\theta=\frac{\varphi(t-\frac{r-r_0}{C})}{r}.$$

After simple transformations we get:

(1.8)

$$U_r=-\frac{C}{r}f'\left(t-\frac{r-r_0}{C}\right)-\frac{C^2}{r^2}f\left(t-\frac{r-r_0}{C}\right),$$

$$V_r=-\frac{C}{r}f''\left(t-\frac{r-r_0}{C}\right)-\frac{C^2}{r^2}f'\left(t-\frac{r-r_0}{C}\right),$$

$$\theta=\frac{\varphi(t-\frac{r-r_0}{C})}{r},$$

$$\theta=\frac{\varphi(t-\frac{r-r_0}{C})}{r},$$

where V_r - radial displacement speed.

The resulting equation includes the unknown function *f (t)*, which is the solution to the differential equation

(1.9)

$$-\rho(t) = \frac{1}{r_0}\left[(\lambda+2\mu)f''(t) + \frac{4\mu C}{r_0}f'^{(t)} + \frac{4\mu C^2}{{r_0}^2}f(t)\right].$$

where P_0 - maximum pressure on the walls of the charge cavity;

$$P(t) = \frac{P_0 t}{t}[\eta(t) - \eta(t-t_{max})] + P_0 e^{-\delta(t-t_{max})}\eta(t-t_{max}), \quad (1.10)$$

Assuming that the pressure in the well changes according to the law (1.2), we represent it using the function *ij (t)* in the following way:

8 is an indicator of pressure decay in the charge cavity.

(1.11)

$$\eta(t) = \begin{cases} 0, t \le 0; \\ 1, t > 0, \end{cases}$$

$$f(0) = f'(0) = 0.$$

If condition (1.16) is satisfied, then equation (1.13) in operational form is transformed to the form :

(1.12)

$$-\frac{1}{r_0}\left[(\lambda+2\mu)p^2 + \frac{4\mu C}{r_0}p + \frac{4\mu C^2}{{r_0}^2}\right]x(p) =$$

From here

$$1 - e^{-t_{max}p} \qquad e^{-t_{max}(\rho-\delta)}$$

$$x(p) = -\frac{P_0 r_0}{\lambda+2\mu}\left\{\frac{1-e^{-t_{max}p}}{t_{max}\rho^2[(p+\gamma)^2+\omega^2]} + \frac{e^{-t_{max}(\rho-\delta)}}{(\rho+\delta)[(p+\gamma)^2+\omega^2]}\right\},$$

Where

$$\omega = \frac{2C\sqrt{\mu(\lambda+\mu)}}{r_0(\lambda+2\mu)};\ \gamma = \frac{2\mu C}{r_0(\lambda+2\mu C)}.$$

Having determined the original of function (4.18), we obtain:

$$f(t) = -\frac{P_0 r_0}{\lambda+2\mu}\left[\frac{D+Ct+e^{-\gamma t}(A\cos\omega t+B\sin\omega t)}{t_{max}}\right]\eta(t) -$$

$$-\left\{\frac{D+C(t-t_{max})+e^{-\gamma(t-t_{max})}[A\cos\omega(t-t_{max})+B\sin\omega(t-t_{max})]}{t_{max}}\right\}\eta(t-t_{max}) +$$

$$+e^{\delta t_{max}}\{A_1 e^{-\delta(t-t_{max})} + [B_1\cos\omega(t-t_{max}) + C_1\sin\omega(t-t_{max})]\cdot$$

$$\cdot e^{-\gamma(t-t_{max})}\eta(t-t_{max})\},$$

Where

$$A = -D = \frac{2\gamma}{\left(\gamma^2+\omega^2\right)^2}; B = \frac{\gamma^2-\omega^2}{\left(\gamma^2+\omega^2\right)^2}; C = \frac{1}{\gamma^2+\omega^2};$$

$$A_1 = -B_1 = \frac{1}{\frac{4\mu C}{r_0}\delta - (\lambda+2\mu)\delta^2 - \frac{4\mu C^2}{{r_0}^2}};$$

$$C_1 = \frac{\left[\frac{4\mu C}{r_0} - (\lambda+2\mu)\delta\right] r_0}{2C\left[\frac{4\mu C}{r_0}\delta - (\lambda+2\mu)\delta^2 - \frac{4\mu C^2}{{r_0}^2}\right]\sqrt{\mu(f+\mu)}}.$$

To simplify the research, we assume that the rise time of the maximum pressure in the charge cavity is zero, then expression (1.19) will be transformed to the form:

$$f(t) = -\frac{P_0 r_0}{\lambda+2\mu}\left[A_1 e^{-\delta t} + (B_1 cos\omega t + C_1 sin\omega t)e^{-\gamma t}\right].$$

Having determined the first and second derivatives of function (1.20) and substituting their values into (4.9) - (4.12), we obtain dependencies for determining the rate of displacement of radial and tangential stresses over time at various distances from the center of the charge.

Per unit of time, to simplify calculations and make comparisons clearer, the amount of time is expressed in relative units:

$$t' = \frac{Ct}{r_0} - \frac{r-r_0}{r_0}.$$

From the analysis of the obtained dependencies (1.9) - (1.12) it follows that the radial and tangential stresses consist of an acoustic component (inversely proportional to the first power of the distance), a quasi-hydrodynamic component (inversely proportional to the square of the distance) and a quasi-static component (inversely proportional to the cube of the distance).

If the pressure in the charge cavity changes σ according to the law $P_0 e^{-\sigma t}$, then at the moment the wave arrives at a given point in the medium, compressive tangential and radial stresses arise in it, and the formation of tensile stresses lags behind the wave front. Near the charge cavity $(r = 1+4 r_0)$ tensile tangential stresses exceed compressive stresses_at the wave front and since_The temporary resistance of rocks to tension is less than to compression, so the first cracks will appear under the action of tensile tangential stresses in the radial direction.

Since the formation of tensile tangential stresses lags behind the wave front, this is one of the reasons why the radial crack front lags behind the stress wave front.

In the zone adjacent to the charge, tensile stresses in the radial direction do not arise and only at a distance $r = 5 r_0$ at $\sigma = 1000$ 1/sec, tensile stresses appear in the radial direction. Having arisen at a certain distance, tensile radial stresses increase with distance and then decrease. Under the influence of these stresses, concentric cracks can appear at a distance several times greater than the radius of concentric cracks caused by the action of compressive radial stresses.

The filmogram we obtained of the process of destruction of a glass model by an explosion of heating element confirms the presented picture of crack formation.

The distance at which tensile radial stresses occur depends not only on the physical and mechanical properties of the rock, but also on the nature of the application of the load in the charge cavity.

As *σ increases* , the time of action of the effective pressure of the charge cavity decreases, which in turn leads to a decrease in the time of action of the positive phase of the stress wave.

As *σ increases* , the magnitude of the maximum tensile tangential stresses and concentric cracks formed under the action of radial tensile stresses also decreases.

From the analysis of dependencies (1.9) - (1.12) it follows that with an increase in the radius of the charge with the same nature of pressure attenuation in the well, the duration of the positive phase of the wave and the magnitude of the maximum tangential tensile stresses increase. This in turn leads to an increase in the rate of crack development.

From the analysis of the solution to the wave equation (1.7) it follows that the formation and distribution of the stress field is significantly influenced by the time of rise of the maximum pressure in the charge cavity. In Fig. 1.3 and 1.4 show graphs of changes in the parameters of voltage waves over time at various distances from the charge at t_{max} = 4 µsec and t_{max} = 31 µsec.

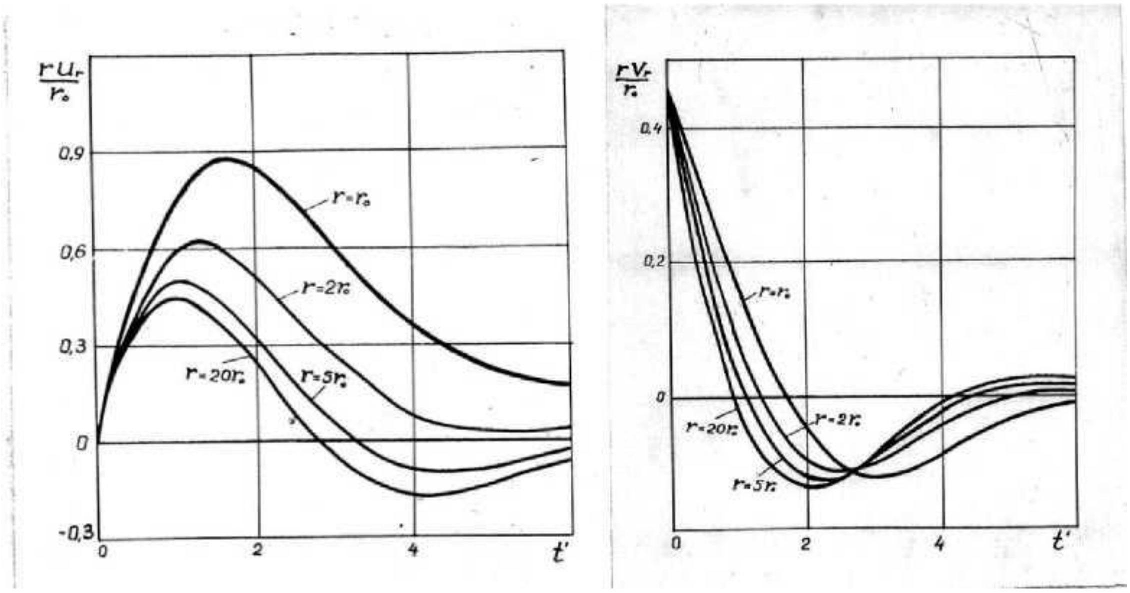

Figure 1.1 - Change in the radial velocity of displacement (a) and displacement (b) over time at various distances at σ =10000, 1/sec

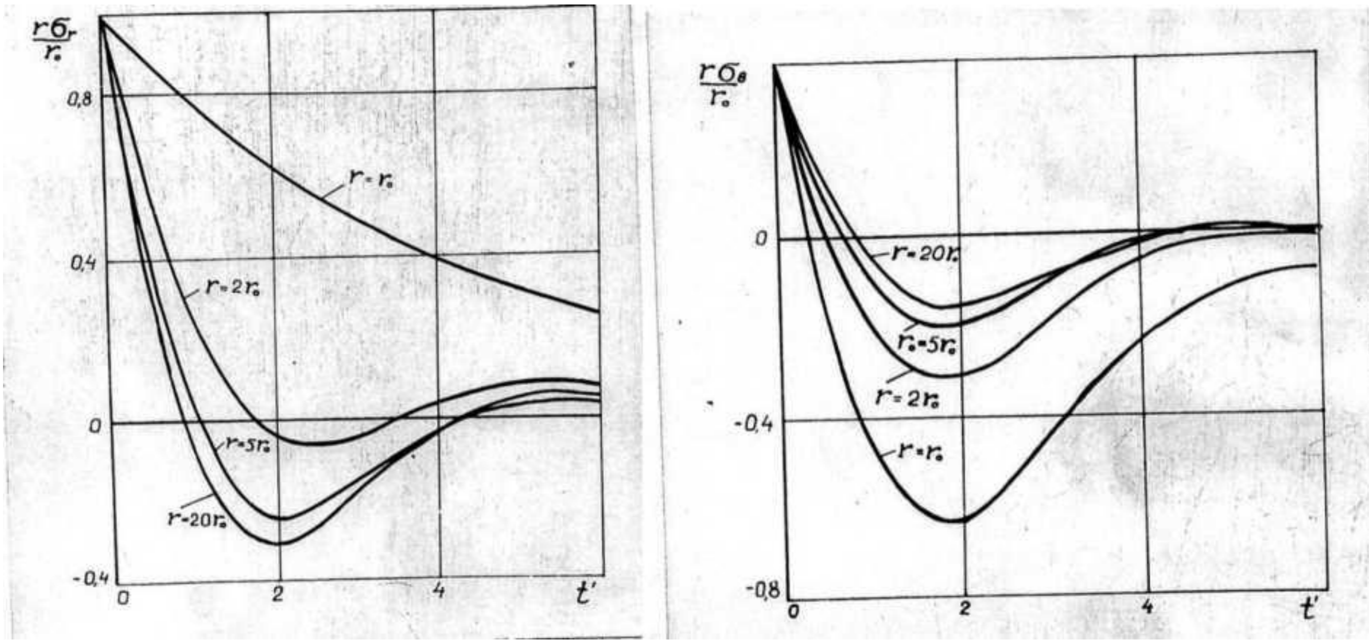

Figure 1.2 – Change in radial (a) and tangential (b) voltages at various distances at δ=10000.1/sec.

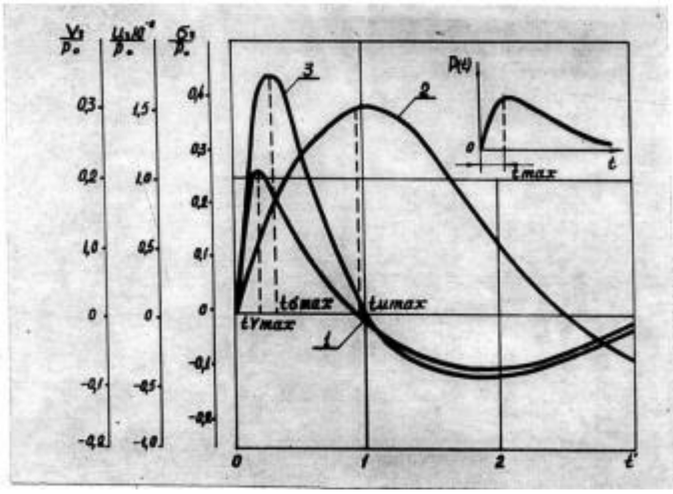

Figure 1.3 – Change in radial displacement speed (1), displacement (2) and radial voltage (3) in time at tmax= 4 μs

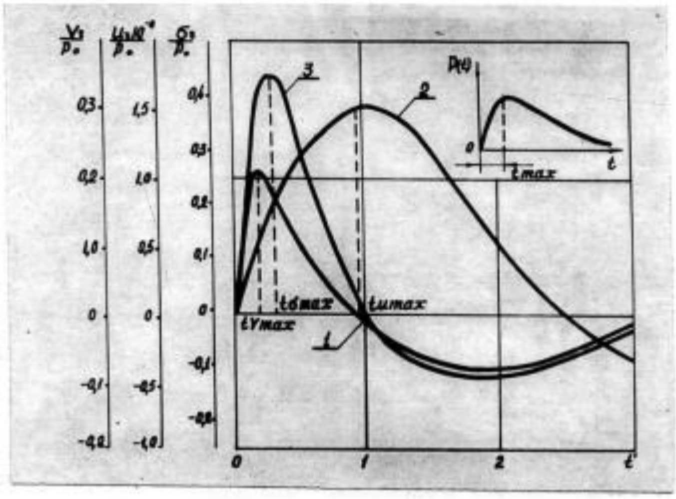

Figure 1.4 – Change in radial displacement speed
(1), displacement (2) and radial voltage (3) in time at tmax= 31 μs

A comparison of the parameters of stress waves at different times of rise of the maximum pressure in the charge cavity shows that with an increase in the time of rise of the maximum pressure in the charge cavity, the time of rise of the maximum of radial stresses also increases.

The higher the modulus of elasticity of the medium and the shorter the rise time of the maximum pressure in the charge cavity, the smaller the difference in the rise time of the maximum displacement speed and radial stress. With an increase in the rise time of the maximum pressure in the charge cavity and a decrease in the elastic modulus, the rise time of the maximum radial stress approaches the time of rise of the maximum displacement. The rise time of the maximum radial stress at a given point in the medium is always greater than t $t_{V_r max} \leq t_{\sigma_r max} < t_{U_r max}$, te, but less than the time of rise of the displacement to the maximum value, i.e. satisfies the inequality:

Where is tvr max , t σ r max , tur max , the rise time to the maximum value of the displacement speed, radial stress and displacement, respectively.

As the pressure rise time in the charge cavity increases, the intensity of the attenuation of the maximum stresses and the maximum displacement speed with distance decreases.

Thus, as a result of research, it has been established that with increasing time of pressure rise in the charge cavity, the intensity of attenuation of maximum stresses and maximum displacement speed with distance decreases.

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