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THE FORMATION OF SUBSURFACE ROCK BREAKDOWN ZONES AROUND WORKINGS DURING THEIR DRIVING BY DRILLING AND BLASTING†

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The stress distribution around a cylindrical cavity in a solid mass during the impulsive application of a radial pressure on its contour has been found. This enables one to establish the formation of subsurface breakdown zones due to radial tensile stresses which are formed after the passage of a compression wave, the maximum value of which is realized at a certain distance from the contour of the cavity and also to elucidate the mechanism of the multiply repeated process of the formation of subsurface breakdown zones which has been experimentally revealed under natural conditions [1] and has not as yet been explained from the position of the static manifestation of rock pressure.

1. THE OCCURRENCE OF COMPRESSION WAVES WHEN A LOAD IS INSTANTANEOUSLY APPLIED TO A CYLINDRICAL CAVITY UNDER CONDITIONS OF PLANE DEFORMATION

WE SHALL seek the solution of the equation of motion for an isotropic elastic solid mass

$$(\lambda+\mu)\,\mathbf{grad}\ \mathbf{div}\ U+\mu\nabla^2 U=\rho U^{\cdot\cdot} \qquad (1.1)$$

(λ and μ are Lamé constants, ρ is the density of the medium and U is the displacement vector), taking account of the polar symmetry using a scalar potential φ which is related to the displacements by the Helmholtz dependence. When this potential is used, Eq. (1.1), after a Laplace transformation, can be represented in the form

$$\partial^2\bar\varphi/\partial r^2+r^{-1}\partial\bar\varphi/\partial r=\bar\varphi s^2/C_1^2 \qquad (1.2)$$

Hence φ and s are the images of the scalar potential and time in the Laplace transformation, r is the polar radius and C_1 is the velocity of propagation of a longitudinal wave.

By taking account of the fact that a function of the form of

$$\bar\varphi=AK_0\,(sr/C_1)$$

is a solution of Eq. (1.2) and using the well-known expressions which relate the strains and the stresses in terms of the potential [2], we determine the Laplace transformed radial displacements as well as the radial and shear stresses

$$\bar U=-ASK_1\,(Sr),\quad \bar\sigma_r=A\,(2\mu+\lambda)S^2K_0\,(Sr)+A2\mu Sr^{-1}K_1\,(Sr),$$
$$\bar\sigma_\theta=-A2\mu Sr^{-1}K_1\,(Sr)+AS^2\lambda K_0\,(Sr),\quad S=s/C_1$$

Here, K_0 and K_1 are MacDonald functions of the zeroth and first order and A is a constant coefficient which is determined from the boundary conditions.

On satisfying the boundary conditions on the contour of the cavity a for the case of an instantaneously applied pressure P_0 (using a Heaviside function) $\sigma_r=-P_0H(t)$ and, also, by using asymptotic expansions of the MacDonald functions, subject to the condition $r^2S^2\gg 1$, we obtain

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$$\bar{U} = We^{-S(r-a)}(S + r^{-1})N^{-1}s^{-1}, \quad \bar{\sigma}_r = -We^{-S(r-a)}[S(2\mu+\lambda) + 2\mu r^{-1}]N^{-1}Ss^{-1},$$
$$\bar{\sigma}_\theta = -We^{-S(r-a)}[\lambda S^2 - 2\mu(Sr^{-1} + r^{-2})]N^{-1}s^{-1}, \quad W = P_0\sqrt{a/r}, \quad N = S[S(2\mu+\lambda) + 2\mu/a] \tag{1.3}$$

Applying an inverse Laplace transformation to (1.3) we obtain the solution

$$U = \frac{WM}{2\mu}\left(t - \frac{r-a}{C_1}\right), \quad \sigma_r = -W\left[1 - M\left(t - \frac{r-a}{C_1}\right)\frac{r-a}{ar}\right]$$
$$\sigma_\theta = -W\left[\frac{\lambda M}{2\mu C_1} - M\left(t - \frac{r-a}{C_1}\right)\left(\frac{1}{r} + \frac{\lambda M}{2\mu C_1 a}\right)\right], \quad M = \frac{2\mu C_1}{2\mu+\lambda} \tag{1.4}$$

which determines the distribution of the stresses and strains in the solid mass during the action of a pressure Δt on the contour of the cavity.

2. THE STRESS DISTRIBUTION IN THE TRAILING PART OF THE COMPRESSION WAVE WHEN THE ACTION OF THE PRESSURE ON THE CAVITY CONTOUR CEASES

Let us now consider the solution in the case when the action of the pressure on the contour of the cavity ceases after a definite interval of time Δt. In order to do this, we apply the same pressure to the contour of the cavity but with opposite sign. Then, on adding the solution of (1.4) to the new solution, we have

$$U = WM\Delta t/(2\mu), \quad \sigma_r = WM\Delta t\,(r-a)/(ar)$$
$$\sigma_\theta = WM\Delta t\,(r^{-1} + \lambda(2\mu+\lambda)^{-1}a^{-1}) \tag{2.1}$$

It can be seen from (2.1) that, after the passage of the compression wave in the solid mass, radial tensile stresses arise which will increase as the distance from the working contour becomes greater. In order to determine their maximum value, let us consider another solution which determines the tensile stresses in the trailing part of the compression wave.

Tensile stresses arise in the zone of the solid mass close to the cavity contour after the passage of a compression wave due to the accumulation of deformation potential energy in it. After the passage of the wave and the removal of the forces, these segments of the solid mass will commence a reverse motion. The above-mentioned process can be described using the following equivalent system. Let us cut out an annular zone of the solid mass which will define the precontour zone after the passage of a compression wave through it and, in order to specify the same displacements in it as actually occur in practice, we apply radial stresses to its internal and external surfaces. When some simple operations are carried out, we obtain the value of the internal pressure P_a and the external pressure P_b on the surface of the annulus

$$P_a = -Q\left(\frac{a^2+b^2}{a} - 2b\sqrt{a/b}\right)$$
$$P_b = -Q\left(2a - \sqrt{\frac{a}{b}}\,\frac{a^2+b^2}{b}\right); \quad Q = \frac{EP_0C_1\Delta t}{(2\mu+\lambda)(b^2-a^2)} \tag{2.2}$$

Here, E is the modulus of elasticity of the rocks and b and a are the external and internal radii of the annulus.

Then, on removing the stresses on the internal contour of the annulus by instantaneously applying the same pressure of the opposite sign to it, we obtain the conditions which are completely equivalent to the real processes in the precontour zone of the solid mass.

We determine the time during which an impulsive load will be applied to the internal contour from the condition of the equality of the dynamic and static displacements on the internal contour

$$t = (2\mu+\lambda)(b^2-a^2)\left[EC_1(a + b^2/a - 2b\sqrt{a/b})\right]^{-1} \tag{2.3}$$

By taking account of the fact that the external radius of the annulus is defined by the expression $b = a + tC_1$ and substituting expression (2.3) into it, we get

$$b = a\left[\sqrt{2 - \frac{4\nu^2}{1-\nu} + \frac{\nu^4}{(1-\nu)^2}} - 1 + \frac{\nu^2}{1-\nu}\right]^{-1} \tag{2.4}$$

from the solution of the resulting equation by expanding it in a Taylor series and neglecting terms of higher orders of smallness. We also get the value of the maximum tensile stress on its external boundary which is determined from the condition for superimposing the static and dynamic stresses (ν is Poisson's ratio)

$$\sigma_r = -Q\left[4a - \sqrt{\frac{a}{b}}(a^2 + b^2)\left(\frac{1}{a} + \frac{1}{b}\right)\right] \tag{2.5}$$

The value of the parameter b, established from (2.4), will determine the zone with the maximum value of the tensile stress, since it corresponds to the maximum value of the potential energy of the annular zone on the outer boundary of which the reverse motion only starts while it has already terminated on the internal boundary. We also point out that the value of the parameter b must not exceed a value of $3a$, which corresponds to the maximum values of the tensile stresses determined from expression (2.1), while the constraint imposed on the asymptotic solution must be strictly satisfied only at the instant when the pressure pulse acts. After its cessation the resulting equation fairly accurately describes the stress distribution in the compression wave (1.4) and also in its trailing part (2.1), up to the instant of the attainment of the maximum values of the radii tensile stresses in the zone at a distance of $b - a$ from the contour of the cavity. The latter is confirmed by the good convergence of the results of the determination of the tensile stresses using expressions (2.1) and (2.5).

Hence, after the passage of a compression wave in the solid mass, tensile stresses arise which will increase as the distance from the working contour becomes larger. These stresses play an important role in the formation of the zones of structural disintegration of the rocks on account of the fact that, during the passage of the compression wave, the rocks are in a state of compression from every side and, when account is taken of the static concentration of the stresses from the rock pressure which is close to the bulk pressure, they can withstand greater stresses without fracturing while the radial tensile stresses which occur give rise to the fracturing of the rocks even when they have exceedingly small values.

The occurrence of zones with intense tensile stresses in the depth of the solid mass at a certain distance from the working contour can lead to the fracture of the rocks and the formation of cracks parallel to the working contour, that is, to structural disintegration of the rocks which is confirmed by the data from experimental investigations [1].

3. THE MECHANISM OF THE FORMATION OF CERTAIN FRACTURE ZONES THROUGHOUT THE DEPTH OF A SOLID MASS

After the passage of a compression wave, the precontour zone of a solid mass has residual radial displacements, that is, it possesses a potential energy which is a source of the occurrence of tensile stresses at the beginning of the motion of the annular zone into the initial state. Their growth on becoming more distant from the working contour is associated with the fact that, at a large distance from the working contour but at a distance which does not exceed $b - a$, internal annular zones which form tensile stresses, have a greater potential energy.

It is then obvious that an unloading of the solid mass occurs after the formation of a first fracture zone at a certain distance from the working contour r_1, that is, the tensile stresses fall to zero while the potential energy is expended in fracturing the rocks. From this instant, a new accumulation of potential energy begins together with a new increase in the tensile stresses. We determine the nature of the stress distribution in the solid mass after the formation of the first fracture zone by considering a solid mass with a new cavity contour r_1 with a load

$$P = -W(1 - Mf(r_1, a)\tau)\sqrt{\frac{r}{r_1}}, \quad 0 \leqslant \tau \leqslant \Delta t, \quad f(r_1, r) = \frac{r_1 - r}{r_1 r} \tag{3.1}$$

acting on the surface.

By taking account of expression (2.1), we establish the distribution of the stresses in the trailing part of the compression wave

$$\sigma_r = -W\left[Mf(r_1, r) - Mf(r_1, a)\int_0^{\Delta t} Mf(r_1, r)\tau d\tau\right] = WMf(r_1, r)\Delta t\left(1 - Mf(r_1, a)\frac{\Delta t}{2}\right) \tag{3.2}$$

Let us now establish the stress distribution after the formation of a second fracture zone (when $r = r_2$), while allowing for the fact that the distance to the first fracture must be far less than $b - a$ since, if the first fracture zone is located in the zone of maximum tensile stresses at a distance of $b - a$ from the contour, no fracturing will occur in the second or especially the third and by representing the pressure on the contour r_2 in a simplified form, neglecting terms of higher orders of smallness, we shall have

$$P = -W\sqrt{\frac{r}{r_2}}\,[1 - Mf(r_1, a)\tau - Mf(r_2, r_1)\tau], \quad 0 \leqslant \tau \leqslant \Delta t \tag{3.3}$$

We determine the stress distribution for the third zone in a similar manner

$$\sigma_r = -WMf(r_2, r)\,\Delta t\,[1 - Mf(r_1, a)\frac{\Delta t}{2} - Mf(r_2, r_1)\frac{\Delta t}{2} \tag{3.4}$$

4. THE FORMATION OF ROCK STRUCTURAL DISINTEGRATION ZONES AROUND WORKINGS WHEN THEY ARE DRIVEN BY THE DRILLING AND BLASTING METHOD

We shall consider the following example. A mine working of circular shape with a radius $a = 3$ m is located in an isotropic elastic solid mass with Poisson's ratio $\nu = 0.2$ and tensile strength $R = 1.7$ MPa. The rate of propagation of longitudinal waves in this medium is $C_1 = 1000$ m/s.

In the construction of the mine working and the extraction of the rock mass by the drilling and blasting method, let us consider the action on the solid mass of just one of a series of explosions of the mapping blast holes which create a pressure on the contour of the working with an intensity of $P_0 = -50$ MPa which is instantaneously applied and maintained over a period of time $\Delta t = 0.9$ ms.

Then, by determining the tensile stresses in the solid mass after the passage of the compression wave, we establish the first fracture zone where the tensile stresses exceed the ultimate tensile strength of the rock which is at $r_1 = 3.6$ m. However, since the thickness of the precontour layer of the first fracture zone will be far smaller than $b - a$, a second ($r_2 = 4.75$ m) and a third ($r_3 = 8$ m) fracture zone will subsequently be formed.

Hence, on producing an impulsive action which is instantaneously applied to the contour of the cavity, a compression wave propagates into the solid mass and, after the passage of this wave, tensile stresses occur. They can lead to the formation of subsurface zones where fracturing of the rocks occurs, as has been found experimentally [1].

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