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EFFECT OF A CAMOUFLET EXPLOSION ON FILTRATION CHARACTERISTICS OF A BRITTLE MEDIUM

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At the present time, explosions are finding increasing use in the national economy. In particular, they are widely used for increasing the production of oil and gas wells. Here, there is great interest in the filtration properties of the medium surrounding the explosion. It should be noted that the theoretical study of filtration properties of media is especially important, since their experimental study is very difficult.

However, at the present time, there are practically no works in which the filtration characteristics of media after an explosion are computed on the basis of the physical picture of the action of a camouflet explosion on the surrounding rock. Thus, e.g., in [1] an attempt is made to describe phenomenologically using a single function, the coefficient of permeability of the medium after a camouflet explosion both in the pulverization zone and in the zone of radial fracturing. But the results of this work do not agree satisfactorily with the experiments [2], since in the investigation concrete mechanisms for dynamic action of the explosion on the medium were not taken into account.

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In the present work, we determine the filtration properties of a medium after a camouflet explosion in a brittle weakly porous rock with a low starting coefficient of permeability. In examining this problem, it is necessary to take into account the fact that with a camouflet explosion three zones that differ considerably as to their structure are formed: a pulverization zone, a radial fracture zone, and an elastic deformation zone [3]. In the pulverization zone, due to large stresses on the shock front, there is a fracture of rock. Subsequent motion of the pulverized medium loosens it up. This loosening up can be explained by the dilatancy effect [4], which is manifested in a change in the density of the medium under the action of shear deformations. At small depths, a zone with radial fracture, arising due to tensile azimuthal stresses, can border the pulverization zone. In order to estimate the porosity in this zone, it is possible to use the model of elastic rods [3]. And, finally, it can be assumed that in the elastic deformation zone the changes in the properties of the rock are small.

The coefficient of permeability, computed on the basis of these assumptions as to the nature of the action of the camouflet explosion on the surrounding medium, is compared with the experimental data from the "Hardhat" explosion [2].

Pulverization Zone. Let us examine the filtration properties of a medium in the pulverization zone. There exist in the literature a large number of theoretical and empirical expressions for calculating the coefficient of permeability of fractured rock; however, the most widely accepted one is the formula of Kozen [1, 5, 6]:

$$K = C/\tau \cdot m^3/\Sigma^2, \quad (1)$$

where m is porosity; Σ, specific surface area of the pieces; S, constant, related to the geometry of the sections of the porous channels; τ, coefficient of tortuosity. In the case when the shape of the pieces is close to cubic, the specific surface area can be related to the characteristic size of a piece $\Sigma = 6(1 - m)d$. Then, assuming the largest typical values for C and τ and ($C \simeq 0.5$, $\tau \simeq 2$), from relation (1) we obtain

$$K = 0.7 \cdot 10^{-2}\ m^3 d^2/(1 - m)^2. \quad (2)$$

Thus, in order to determine the filtration properties of a medium in the pulverization zone, it is necessary to know its porosity as well as the sizes of the fractured rock pieces.

In the present work, we examine the filtration properties of a medium after an explosion in initially monolithic brittle rock. We assume that such a medium is a weakly porous rock, e.g., granite. The porosity in the pulverization zone arises due to fracture and subsequent motion of the fractured rock with the explosion. The basic mechanism for loosening up the fractured rock is the dilatancy effect, related to the change in the specific volume due to shearing deformations [4]. In this case, neglecting the elastic compressibility, the change in porosity m can be represented in the form

$$dm = (1 - m)\Lambda|d\gamma|,$$

where Λ is the coefficient of dilatancy; $d\gamma$ is the change in the shearing stresses.

The problem of the explosion in a dilating medium was solved in [7] for the case of a constant dilatancy coefficient. Using the results of this work, in the case of monolithic rock, we obtain the following expression for the porosity:

$$m(r) = 1 - \left[1 - \left(\frac{a}{r}\right)^n + \left(\frac{a_0}{r}\right)^n\right]^{\Lambda}, \quad n = 3/(1 + \Lambda), \quad (3)$$

where a_0 and a are the starting and final radii of the cavity. We note that at large distances from the boundary of the cavity, the porosity changes according to a power law $m(r) \sim r^{-n}$.

In order to estimate the average size of the pieces of pulverized rock, let us assume that the fracturing occurs along the front of the shock wave as a result of the development of microscopic cracks that are already present in the rock. According to the criteria of Griffiths [8], only those microscopic cracks will grow when size exceeds some limiting length $l(\sigma)$, depending on the applied stress, according to the law

$$l(\sigma) = k/\sigma^2. \quad (4)$$

Then, the size of a piece of pulverized rock will be determined by the distance between the growing microcracks. Introducing the function $N(l)$, determining the density of microcracks with length exceeding l, taking into account (4), we obtain an expression for the average size of a piece of pulverized rock

$$d(\sigma) = N^{1/3}(l(\sigma)) = N^{1/3}(k/\sigma^2), \tag{5}$$

where σ is the stress at the front of the wave. Thus, knowing the density of microcracks and the nature of the change in σ with distance, it is possible to determine the distance dependence of the average size of a piece.

The following calculations will be carried out assuming that the function $N(l)$ has an exponential form. In this case, from the (5), it is possible to obtain the expression

$$d(\sigma) = d_0 \exp\left(\frac{\sigma_*^2}{\sigma^2}\right), \tag{6}$$

where d_0 is the minimum distance between microcracks, while the quantity σ_* is determined by the average length of a microcrack:

$$\sigma_*^2 = k/\langle l \rangle.$$

This quantity is an internal parameter of the medium and does not depend on the intensity of the explosion.

Expression (6) is valid only when the duration of the loading wave significantly exceeds the time of growth of cracks. In the opposite case, microcracks do not have time to grow and pulverization will not occur. For this reason, the maximum size of a piece will be determined by the width of the loading wave, which in the presence of the explosion turns out to be of the order a_0. In this manner, for pieces with maximum size d_m in the pulverization zone the following relation is valid:

$$d_m = \alpha a_0, \tag{7}$$

where the quantity $\alpha \lesssim 1$.

Using relations (6) and (7), we obtain an expression that determines the stress in the wave on the pulverization zone boundary ($r = R_1$):

$$\sigma(R_1) = \sigma_* \ln^{-1/2}(d_m/d_0) = \sigma_* [\ln(\alpha a_0/d_0)]^{-1/2}. \tag{8}$$

This quantity can be identified with the effective strength of the rock in the presence of the explosion. As can be seen, it depends quite weakly on the intensity of the explosion $W(\sigma(R_1) \sim \ln^{-1/2}(W))$ and as W increases, it smoothly decreases.

The quantity $\sigma(R_1)$ determines the relation between the size of the pulverization zone and the final radius of the cavity [3]:

$$R_1 = a\left(\frac{E}{\sigma(R_1)\, n}\right)^{1/n} = a\left(\frac{E}{\sigma_* n}\right)^{1/n} [\ln(d_m/d_0)]^{1/2n}. \tag{9}$$

It is easy to see that the ratio R_1/a also depends on the scale of the explosion. For small variations in the intensity of the explosion, this relation can be viewed as constant. At the same time, relation (9) shows that it is necessary to treat the transfer of laboratory test results to natural explosions with care.

In order to determine the dependence of the size of pieces and, therefore, the coefficient of permeability on distance, it is necessary to know the nature of damping of the shock wave with distance. As the results of numerous calculations show, the shock wave is damped in the pulverization zone according to a power law $\sigma(r) \sim r^{-\beta}$. Then, taking into account the relation between the Lagrangian and Euler particle radii [7], from relations (6) and (8), we obtain

$$d(r) = d_0 \exp\left\{\left(\frac{\xi^n + \xi_0^n - 1}{\xi_*^n + \xi_0^n - 1}\right)^{2\beta/n} \ln(d_m/d_0)\right\}, \tag{10}$$

where the following dimensionless distances have been introduced: $\xi = r/a$, $\xi_0 = a_0/a \ll 1$, and $\xi_* = R_1/a$. In expression (10), the quantity $\xi_0{}^n$ can be neglected if we are not interested in the region in direct proximity to the surface ($r - a \sim a\xi_0{}^n/n \sim 10^{-3}a$).

Substituting relations (3) and (10) into (2) and taking into account the fact that $m \ll 1$, we obtain the final expression for the coefficient of permeability in the pulverization zone:

$$K_1(\xi) = 0.7\cdot 10^{-2} d_0^2 [1-(1-\xi^{-n})\Lambda]^3 \exp\left[2\left(\frac{\xi^n-1}{\xi_*^n-1}\right)^{2\beta/n} \ln\frac{d_m}{d_0}\right]. \quad (11)$$

As can be seen from this relation, the behavior of the permeability coefficient in the pulverization zone as a function of distance is determined by the competition between two factors. On the one hand, decrease in porosity with increasing ξ leads to a decrease in the permeability coefficient. The nature of this relation has a universal form and does not depend on the scale of the explosion (if the condition $\xi_0^n \ll 1$ is satisfied). On the other hand, an increase in the size of the pulverized rock pieces leads to an increase in the permeability. This dependence is strongly related to the scale of the explosion and is determined by the ratio d_m/d_0.

If the ratio d_m/d_0 is close to one, then $K_1(\xi)$ in the pulverization zone will decrease monotonically with distance. As this ratio increases, in regions of ξ close to ξ_*, the function $K_1(\xi)$ will flatten out. Finally, when the inequality $\ln(d_m/d_0) > 3n/4\beta$ is satisfied, the coefficient of permeability becomes a nonmonotonic function of distance: in the pulverization zone a minimum appears in the function $K_1(\xi)$. The coordinate of this minimum assuming that $\xi_m^n \gg 1$ will be given by the relation

$$\xi_m = \xi_* \left[\frac{3n}{4\beta \ln(d_m/d_0)}\right]^{1/2\beta}.$$

As can be seen from the expression presented, as the scale of the explosion increases, the coordinate of the minimum will shift toward shorter distances.

<u>Radial Fracture Zone</u>. In many cases with a camouflet explosion, a radial fracture zone can arise beyond the polarization zone. Radial cracks appear due to tensile azimuthal stresses. A quasistatic estimate [3] gives the following relation between the radius of the pulverization zone R_1 and the radius of the radial fracture zone R_2:

$$R_2 = R_1 \sqrt{\frac{\sigma(R_1)}{2\sigma_0 + 3p_0}}, \quad (12)$$

where p_0 is the back pressure; σ_0 is the rupture strength. From this estimate, it is evident that the radial fracture zone forms if the inequality $\sigma(R_1) > 2\sigma_0 + 3p_0$ is satisfied. For fixed values of $\sigma(R_1)$ and σ_0, it follows from this inequality that radial cracks can form only at depths

$$h < (\sigma(R_1) - 2\sigma_0)/3\rho g,$$

where ρ is the density of the rock.

Substituting relation (8) into (12) and neglecting for simplicity the quantity p_0, we obtain a relation between R_2 and R_1 in the form

$$R_2 = R_1 \sqrt{\frac{\sigma_*}{2\sigma_0}} \ln^{-1/4}(d_m/d_0),$$

from which it is evident that the ratio of the radius of the radial fracture zone to the radius of the pulverization zone decreases with increasing scale of the explosion.

Using equality (9), it is possible to relate the radius of the radial fracture zone, which determines the size of the fracture zone, with the radius of the cavity

$$R_2 = \frac{a}{\sqrt{2}} \left(\frac{E^2 \sigma_*^{n-2}}{n^2 \sigma_0^n}\right)^{1/2n} \left(\ln\frac{d_m}{d_0}\right)^{\frac{2-n}{4n}}. \quad (13)$$

Since Λ is always less than 0.5, it follows from expression (13) that as the quantity d_m/d_0 increases the ratio of the size of the radial fracture zone to the size of the cavity decreases. This is explained by the fact that an increase in the ratio d_m/d_0 is equivalent to a decrease in the effective strength of the medium on pulverization. As a result, the volume of the pulverization zone, where the greatest dissipation of energy of the explosion occurs, increases. For this reason, the fraction of the energy of the explosion entering into the formation of the radial cracks decreases, which is what leads to the relative decrease in the radial fracture zone.

In order to calculate the coefficient of permeability in the radial fracture zone, let us assume that the cracks form two mutually perpendicular systems of flat cracks with a density Γ and opening b. Then, the coefficient of permeability will be determined by the relation [9]

$$K = {}^{1}/_{6}b^{3}\Gamma. \tag{14}$$

The quantity $2b\Gamma$ determines the porosity of the rock in the radial fracture zone. For this reason, the physical meaning of expression (14) is the same as that of expression (1). The difference in the coefficients is related to the difference in the geometry of a porous space in the pulverization zone and in the radial fracture zone.

The porosity in the radial fracture zone can be calculated using the approximation of elastic rods [3]. Then, assuming that the stresses have a static character, we obtain

$$b\Gamma = (1-\nu)\frac{\sigma(R_1)}{E}\left(\frac{R_1}{r}\right)^2,$$

where ν is Poisson's coefficient. Substituting this expression into relation (14) and taking into account (8), we obtain

$$K_2 = \frac{(1-\nu)^3}{6}\left(\frac{\sigma_*}{E}\right)^3\left(\ln\frac{d_m}{d_0}\right)^{-3/2}\left(\frac{R_1}{r}\right)^6\frac{1}{\Gamma^2(r)}.$$

In order to determine the dependence of the permeability coefficient on distance in the radial fracture zone, it is necessary to know the law governing the variation of $\Gamma(r)$. Near the pulverization front, the density of cracks is determined by the minimum distance between microcracks d_0. For the rest of the volume of the radial fracture zone, this quantity can be estimated in two ways: 1) constancy of $\Gamma(r)$ with distance in the fracturing zone, the number of radial cracks will in this case by the magnitude of the variable; 2) the number of radial cracks does not change with distance, then $\Gamma(r)$ will vary according to the law

$$\Gamma(r) = \frac{1}{d_0}\left(\frac{R_1}{r}\right)^2.$$

We obtain a final expression for $K_2(r)$ corresponding to the first and second cases in the form

$$K_2(r) = d_0^2\frac{(1-\nu)^3}{6}\left(\frac{\sigma_*}{E\ln^{1/2}(d_m/d_0)}\right)^3\left(\frac{R_1}{r}\right)^6; \tag{15}$$

$$K_2(r) = d_0^2\frac{(1-\nu)^3}{6}\left(\frac{\sigma_*}{E\ln^{1/2}(d_m/d_0)}\right)^3\left(\frac{R_1}{r}\right)^2. \tag{16}$$

Thus, theoretically, in the radial fracture zone, the coefficient of permeability can decrease with distance according to the law $1/r^6$, as well as according to the law $1/r^2$.

It is useful to compare expressions (15) and (16) with relation (11) with $r = R_1$. In this case, we obtain the expression

$$K_1(R_1)/K_2(R_1) = 4.2\cdot 10^{-2}/(1-\nu)^3\cdot(\Lambda n)^3\cdot(d_m/d_0)^2 \approx 0.15(\Lambda n)^3(d_m/d_0)^2,$$

where it was assumed that $\nu = 1/3$. From this relation, it is evident that if

$$d_m/d_0 < 2.5(\Lambda n)^{-3/2}, \tag{17}$$

then the permeability in the pulverization zone will turn out to be less than in the radial fracture zone. The critical value of the parameter d_m/d_0 equals 25 for $\Lambda = 0.2$ and 75 for $\Lambda = 0.1$. Thus, the inequality opposite to inequality (17) can be satisfied only for very intense explosions. In this case, the coefficient of permeability is observed to decrease at the instant of the transition from the pulverization zone to the radial fracture zone. In the remaining cases, with the transition from the pulverization zone to the radial fracture zone the coefficient of permeability should be observed to increase.

Discussion of Results and Comparison with Experiment. Let us examine the basic conclusions that follow from the relations obtained above. First, it turns out that the radius of the pulverization and fracture zones do not satisfy the similarity law $R_i \sim W^{1/3}$, which is usually used in analyzing the fracturing action of an explosion. The deviation from this law is determined by the value of the quantity d_m/d_0. Figures 1 and 2 show, respectively, the ratio of the radii of the pulverization (curve 1 in Fig. 1) and the fracturing zones to

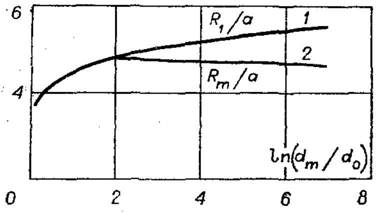

Fig. 1

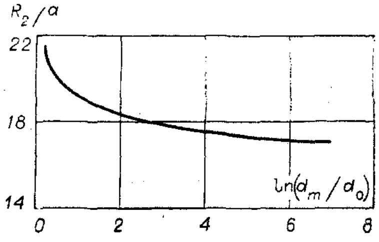

Fig. 2

the size of the cavity as a function of ln (d_m/d_0). In this case, the following values of the parameters were assumed:

$$\sigma_*/E = 5\cdot10^{-3},\quad \sigma_0/\sigma_* = 3\cdot10^{-2},\quad \Lambda = 0.1.$$

It is evident that the strongest dependence on the scale of the explosion is observed for low values of ln (d_m/d_0). In the region of large d_m/d_0, when ln $(d_m/d_0) \gtrsim 2$, the ratios R_1/a and R_2/a can be assumed to be constant.

The behavior of the permeability coefficient is more sensitive to changes in the ratio d_m/d_0. This is related to the fact that the quantity ln (d_m/d_0) enters into the index of the exponent in the expression for $K_1(r)$. Figure 3 shows the dependence of the dimensionless coefficient of permeability ($K_0 = 0.7\cdot10^{-2}\ d_0^2$) on the dimensionless distance $\xi = r/a$ for three values of the quantity ln (d_m/d_0): for curve 1, ln $(d_m/d_0) = 1$; for curve 2, ln $(d_m/d_0) = 3$; for curve 3, ln $(d_m/d_0) = 5$. (In the fracture zone, the curve was constructed according to Eq. (15).) In addition, in calculating the coefficient of permeability, the value of β was taken as equal to 2, which approximately corresponds to damping of maximum stresses in granite [10].

It is clearly evident from Fig. 3 that the nature of the dependence of the coefficient of permeability on distance evolves with the increase in the ratio d_m/d_0. When d_m/d_0 is close to 1, a monotonic decrease is observed in K(r) in the pulverization zone. In addition, due to the high effective strength, greater dispersion of the medium occurs in this case in the radial fracture zone. This is what leads to the fact that a sharp increase in permeability is observed on the zone boundary with a transition into the radial fracture zone.

As the ratio d_m/d_0 increases, the dependence of the permeability coefficient on distance in the pulverization zone becomes nonmonotonic. A characteristic minimum is observed in the curve of $K_1(r)$. The dependence of the relative coordinate of this minimum R_m/a on the value ln (d_m/d_0) is shown in Fig. 1 (curve 2). For $r > R_m$, the coefficient of permeability is observed to increase with distance, which is related with the sharp increase in the size of pulverized rock pieces. At the same time, due to the decrease of the effective strength with increasing d_m/d_0, dispersion in the radial fracture zone decreases, which leads to a decrease in the permeability coefficient in this zone. At the same time, the permeability in the fracture zone can be comparable to the permeability in the pulverization zone (curve 2 in Fig. 3) and even becomes lower (curve 3 in Fig. 3).

We note that the nonmonotonic nature of the distance dependence of the permeability coefficient follows from the theory proposed. However, in some cases the indicated nonmonotonic behavior can turn out to be quite weakly expressed (e.g., curve 2 in Fig. 3).

Unfortunately, due to insufficient experimental data, it is difficult to compare the theoretical results with experimental results at the present time. In the present work, for comparison, we used the results of the "Hardhat" experiment, presented in [2]. In this case, we chose the following values of the parameters: $d_0 = 0.5$ cm, $d_m/d_0 = 20$, $K_0 = 1.75\cdot10^5$.

A graph of the theoretical dependence of the permeability coefficient on distance together with the indicated experimental data is presented in Fig. 4. From the comparison presented, it is evident that it is possible to describe fairly well both the relative dependence of the permeability coefficient on distance and its absolute value. The lack of a sufficient quantity of experimental data does not permit a more definitive answer to the question as to whether or not the nonmonotonic behavior of the permeability coefficient, predicted by the theory, exists, as well as which of the two theoretical functions (15) or (16) better describes the behavior of K(r) in the radial fracture zone.

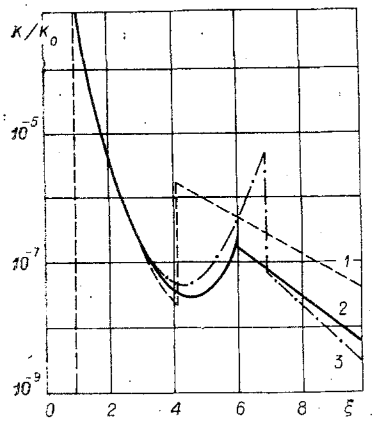

Fig. 3

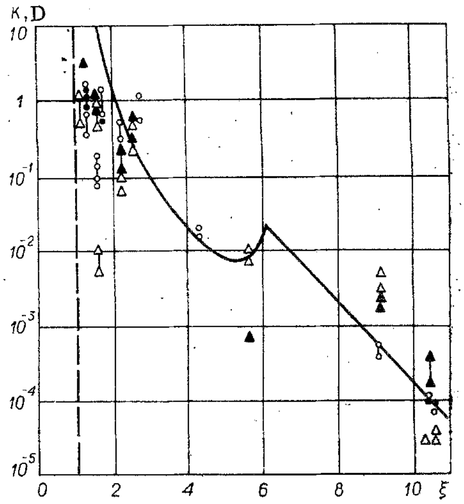

Fig. 4

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