EFFECT OF THE SLIT POSITION AND WIDTH ON THE AMOUNT OF ROCK CRUSHED BY AN EXPLOSION

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A study of the crushing and fracture zones [1] formed by powerful camouflet explosions in ledge rocks shows the advisability of using powerful explosions to crush rocks in mines. This may greatly modify underground mining procedures and heighten the efficiency of mining operations.

To protect adits and other structures from destruction and to increase the volume of crushed ore in a rock mass, horizontal and vertical slits are made. The width of the slit h and its position R_s with respect to the center of the explosion greatly affect the results obtained by the explosion. The tendency to obtain for a charge of given power the maximum screening effect of the slit and the maximum amount of crushed ore (provided that the fragments do not exceed a certain given size) makes it necessary to use computers for the calculations and determination of the optimum values of h and R_s. These effects may be assessed from the viewpoint of a one-dimensional model only when the slit is a spherical layer in the case of a single charge or a cylindrical layer when an elongated charge is used for the explosion. Such a formulation of the problem undoubtedly differs from the common practice of using flat slits for these purposes. However, in our opinion the results of such calculations are of interest and can be used for quantitative assessments.

The mathematical problem was formulated as follows. The energy q, ktons, is initially distributed uniformly in the cavity of a sphere with radius R_c^0, filled with gas, with an equation of state

$$P=(\gamma-1)\rho E.$$

The equation of state of the rock was selected as

$$P=(\gamma-1)\rho E+\frac{\rho_0 C_0^2}{n}\left[\frac{n-\gamma}{n-1}\delta^n+\frac{n(\gamma-1)}{n-1}\delta-\gamma\right].$$

The initial pressure in the rock mass was taken as zero, and the initial density as constant. The rock was assumed to be brittle, which means that it fractured when compressed or eleongated, when the maximum tangential stress τ_{max} reached the critical value

$$\tau_{cr}=0.5Y,$$

where

$$Y=\begin{cases}Y_0+P & \text{when } P<10\text{ kbar }-Y_0,\\ 10\text{ kbar} & \text{when } P\geqslant 10\text{ kbar }-Y_0.\end{cases}$$

Furthermore, to get the fullest picture of the manner in which the rock fractured when elongated, we also assigned the critical stress σ_{cr}. When one of the stresses σ_i reached this value, fissures orthogonal to the direction of this stress appeared in the rock. The volume of the newly formed or existing fissures Θ may vary as time passes. The change in Θ obeys a special differential equation.

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TABLE 1. Dependence of the Size of the Crushing Zone A, Fissure Zone B, and Radius R of Scab on the Tensile Strength σ_{cr} in Absence of a Slit

Calc. No.	σ_{fi}, kbar	R_1, m	R_{fi}, m	M_A, 10^3 tons	M_B, 10^6 tons	$R_1/q^{1/3}$	$R_{fi}/q^{1/3}$	Surface, m	R of scab, m
1	0,08	43,3	87,9	940	6,84	33,8	68,7	130	103
2	0,15	43,3	76,0	940	4,10	33,8	59,4	130	110
3	0,30	43,3	64,6	940	3,82	33,8	50,5	130	119

TABLE 2. Dependence of the Size of the Crushing Zone on the Elastic Limit Y_0 in Absence of a Slit (σ_{cr} = 0.15 kbar)

Calc. No.	Y_0, kbar	R_1, m	M_A, 10^3 ton	$R_1/q^{1/3}$
4	2,2	43,3	940	33,8
5	2,4	32,0	378	25,0

Fig. 1. Schematic representation of the different zones in a medium after an explosion when there is no slit. Cavity ($R \geq R_C$): A) crushing zone ($R_C \leq R \leq R_1$): B) radial fissure zone ($R_1 \leq R \leq R_{fi}$).

The following numerical values of the parameters were used in the calculations: a) in the cavity: $\rho_0 = 1.4$ g/cm^3, γ = 5/3, E_0 = 1500 kJ/g, R_C^0 = 1 m; b) in the rock: ρ_0 = 2.73 g/cm^3, C_0 = 2.55 km/sec, n = 5.3, γ = 1.51, Y_0 = 0.12 kbar, σ_{cr} = 0.15 kbar, Poisson's ratio γ = 0.2. In certain calculations the values of Y_0 and σ_{cr} were varied. We calculated the values of R_s and h for which the volume of crushed rock would be maximum. The calculations were performed according to the "SPRUT" program, intended for the calculation of unsteady motion of compressed media with real properties (elasticity, plasticity, brittleness, compressibility, crushability, etc.). The model of the medium and the difference method are described in [2, 3].

Let us discuss briefly the effects which occur during expansion of the cavity, propagation of the shock wave, and its interaction with the slit.

When t > 0, a shock wave, in the front of which the substance is compressed, is propagated from the surface of the cavity R_C. The tangential stresses increase and reach the critical value $\tau_{max} = \tau_{cr}$, which leads to brittle fracture of the rock (granulation or crushing). With increasing distance from the center of the explosion the amplitude of the shock wave decreases. By the time the wave reaches the radius R_1, it has weakened so markedly that no further crushing occurs in its front.

Behind the front of the shock wave the substance moves at a positive rate, as a result of which the stresses tangential to the spherical surfaces increase. If these stresses reach the critical value $\sigma_2 = \sigma_3 = \sigma_{cr}$, radial fissures appear in the region $R > R_1$. They begin at the surface with radius R_1 and are propagated in the rock toward increasing R. The fissure zone reaches the radius R_{fi}. Here the movement of the substance from the center becomes so weak that the stresses are always less than the tensile strength σ_{cr}.

Let us first examine the case when there is no slit in the medium. The size of the crushing and fissure zones (Fig. 1) depends on the elastic limit Y_0 and the tensile strength σ_{cr}. To determine the character of the change in the size of the crushing and fissure zones with σ_{cr}, three calculations (1, 2, 3) were made; a further two (4, 5) were made to determine how the size of the crushing zone depended on Y_0. The results are given in Tables 1 and 2.

From Tables 1 and 2 we can assess the values of the logarithmic derivatives, which enable us to determine the sensitivity of the model to changes in the values of certain parameters. These derivatives are as follows:

$$\frac{\partial \ln R_{fi}}{\partial \ln \sigma_{cr}} \approx 0.25, \quad \frac{\partial \ln R_1}{\partial \ln Y_0} \approx 0.62.$$

The values of the derivatives show the insensitivity of the model to errors in the determination of σ_{cr} and Y_0, because the relative errors in R_{fi} and R_1 are less than those in σ_{cr} and Y_0; they also enable us to determine the errors of the calculated values of R_{fi} and R_1 if the errors of the experimentally determined values of σ_{cr} and Y_0 are known.

When the shock wave reaches the free surface (inner surface of the slit), the fracture breaks up, as a result of which a rarefaction wave is propagated back again into the medium. This relief wave interacts with the relief wave spreading out from the boundary of the cavity, with the result that in the interference zone one observes scabbing, in the form of both crushed zones and individual scabs (spherically symmetrical). Since this is accompanied by an

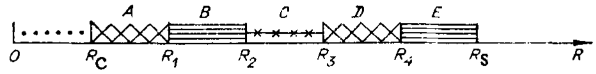

Fig. 2. Cavity ($R \le R_c$): A) crushing zone ($R_c \le R \le R_1$); B, E) zones of radial fissures ($R_1 \le R \le R_2$) and ($R_1 \le R \le R_s$); D) zone of scabbing ($R_3 \le R \le R_4$); C) zone of individual spherical scab fissures against a background of radial fissures ($R_2 \le R \le R_3$) in the case when $R_s < R_{fi}$.

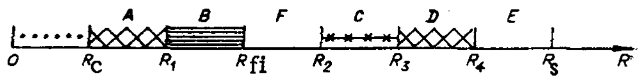

Fig. 3. F and E denote zones of unbroken strong rock ($R_{fi} \le R \le R_2$) and ($R_4 \le R \le R_s$): D) zone of scabbing ($R_3 \le R \le R_4$); C) zone of individual scab fissures ($R_2 \le R \le R_3$) in the case where $R_s \gg R_{fi}$.

TABLE 3. Dependence of Size of Crushing Zones on Position of the Slit (σ_{cr} = 0.15 kbar, Y_0 = 1.2 kbar, ΔR_s = 2 m, R_1 = 43.3 m)

Calc. No.	R_s, m	R_2, m	R_3, m	R_4, m	Maximal fragment size, m	$R_3/q^{1/3}$	$R_4/q^{1/3}$
6	48	43,3	43,3	46,7	0,7	33,8	36,5
7	50	43,3	46,3	48,4	1,0	33,8	37,8
4	55	43,3	49,1	53,5	2,0	38,3	41,8
8	60	48,0	53,2	58,6	4,0	41,6	49,7

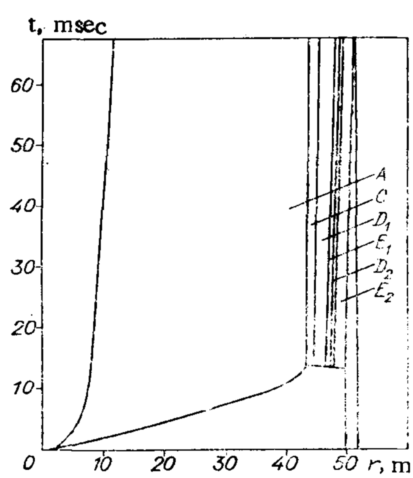

Fig. 4

increase in the speed at which the substance moves away from the center in the layers adjoining the free surface, new sectors with radial fissures may also appear at low R_s. Here two limiting cases must be distinguished.

1. The case when $R_s < R_{fi}$ (we have in mind the value of R_{fi} obtained in absence of a slit). In this case the region of scabs ($R_2 \le R \le R_s$) appears against a background of radial fissures and has the structure represented schematically in Fig. 2.

2. The case when $R_{fi} \ll R_s$. The structure of the region of split-type ruptures ($R_2 \le R \le R_s$) observed in this case is shown schematically in Fig. 3.

In the case when $R_2 < R_{fi} < R_s$, analysis of the zone of disintegration is complicated. Let us examine the pattern of change of zones F, C, D, and E with decreasing R_s, starting with values $R_s \gg R_{fi}$. Firstly we observe a decrease in the size of the F region, and at a certain R_s it disappears. The decrease in R_s is accompanied by an increase in the effect of sphericity during movement of the substance in the E region. This may lead to the appearance of radial fissures in the E region, even before the slit suddenly closes. With a further decrease in R_s, the B zone disappears when R_1 is equal to R_2. In other words, instead of the radial fissure zone we have zone C, in which radial fissures alternate with regions of completely fractured rock. Calculations show that the sizes of the rock fragments in zone C decrease together with decreasing R_s.

At the moment the slit closes, two shock waves appear: a head wave, moving away from the center of the explosion, and a reflected wave, spreading out toward the cavity. Depending on the initial slit width, the rock in the sector ($R_4 \le R \le R_s$) may be crushed in the front of the reflected shock wave. Such crushing cannot occur if the slit is narrow. In the calculations the slit width was varied from 0.9 to 2.5 m, but little change was observed in the amount of fractured rock.

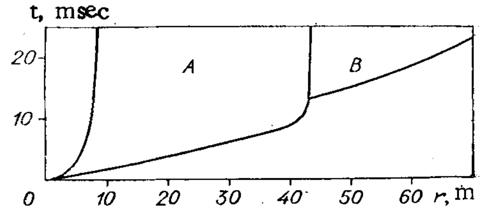

Fig. 5

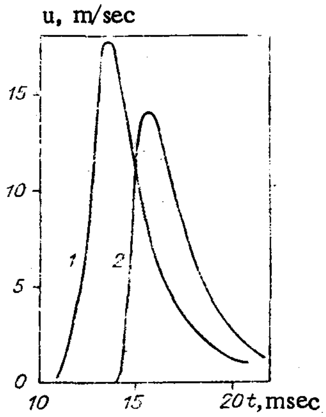

Fig. 6

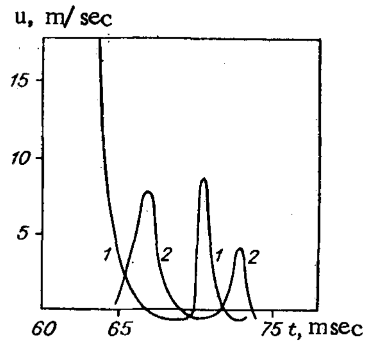

Fig. 7

Note that with decreasing width of the slit, its screening role weakens and the radial fissure zone behind the slit increases. At a slit width $\Delta R_s \geq 1.6$ m, fissure zones are not observed behind the slit.

The calculations show how the size of the crushing zone depends on the position of the slit R_s. Table 3 shows such numerically determined dependences and enables us to determine the position of the slit at which the fragment size will be less than that demanded by technical requirements.

The development of the zones of disintegration as time passes differs markedly in the presence or absence of a slit. The boundaries of these zones are shown in the (r, t) graphs in Figs. 4 and 5 (the notation is the same as in Fig. 2). At the moment the fissure closes, the mean radial speed of the substance U in the fissure region E_2 is 38.6 m/sec. The fracturing coefficient in this region K_f, determined as the ratio of the volume of the substance together with that of the fissure to the volume of the substance, is 1.08. In crushing zone D_2 (Fig. 4) the mean speed at this moment is 35.4 m/sec and the coefficient of porosity K_p, determined as the ratio of the volume of substance together with that of the pores to the volume of the substance, is 1.49. After the slit has closed, the reflected shock wave, moving at a speed approaching that of the speed of sound C_l for longitudinal perturbation, passes through the fissure region E_2 virtually without engendering a decrease in the fracturing coefficient. Part of the substance in the region behind the shock wave front is crushed. As one goes over to the very porous region D_2, the shock wave is almost halted, its speed is much less than C_l, and a considerable part of the energy is expended on pore closure. When this wave reaches the boundary between the D_2 and E_1 zones, it is reflected. The reflected secondary wave is propagated through unbroken substance, then through fissured substance, and overtakes the head shock wave. In the absence of a slit the factors causing secondary shock wave formation are not present. Figures 6 (curves 1 and 2) and 7 plot U vs t at distances of 52 and 60 m from the center of the explosion. It will be seen that in the absence of a slit (Fig. 6) this curve is smooth, but in the presence of a slit (Fig. 7) the curve has a second peak corresponding to the arrival of the secondary wave.

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