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# Measuring the Optimal Focal Distance to Make "Initial" Cavity in the Mass of Solid Natural Resources

Kaerbek Rafkatovich Argimbaev and Isheysky Valentin Alexandrovich
National Mineral Resource University "University of Mines",
21 Line V.O., 2, 199106, St. Petersburg, Russia

**Abstract:** This study describes the complex approach to study the formation process of the cumulative jet and the depth of its implementation into marble and granite in case of rock directional shattering by means of cumulative column charges. As a source of directional explosion we used a cumulative column charge in metal coating. In accordance with the values of measured depths after implementing the cumulative jet into rock plates we got numerical values of "initial" cavity scale depending on the focal distance for different charge types. We describe a model experiment aimed at the study of cumulative jet implementation mechanism and creation of stress concentrator (of the "initial" cavity). There is an X-ray picture here to show the process of implementing cumulative jet into a rock plate and there are results of lab experiments to study the depth of jet implementation at different focal distances. We show the scheme of interaction of separate cumulative jet fragments with the rock. It was revealed how the mass velocities in reflected shock wave for a jet rear side depend on the jet front side velocity for marble and granite. The connection of the implementation depth of the cumulative jet with the distance to the mass became clear.

**Key words:** Blasting operations, blast hole, cumulative column charge, rock mass, cumulative jet, focal distance, "initial" cavity

## INTRODUCTION

At the bottom of the method to shatter rocks directionally we have an idea to form preliminary cavities which are stress concentrators between explosion chambers and their consequential change into main cavities under the quasistatic influence of explosion products. As one of the ways to implement the scheme of rock directional shattering we use cumulative column Charges with a Metal Coating (CCC).

When investigating the process of cumulative jet implementation into different rocks we should consider the jet as an ideal plastic body which acts as a fluid in case it reaches the stress corresponding to the fluidity limit. Consequently we consider the process of cumulative jet braking as an interaction of fluid flows. In this case there is a law of Bernoulli between "cumulative jet-rock" which declares pressure balance on this interface (Orlenko, 2002). Speaking about the rock as a "quasifluid" it is necessary that the pressure on the interface "cumulative jet-rock" must exceed solidity resistant characteristics of rock and inertial forces occurring in it. As an example of the parameter giving an indication of solidity and inertial force, we consider dynamic solidity of rock compression strength.

## MATERIALS AND METHODS

Thus, the condition of penetrating cumulative jet into rock is the pressure dominancy on the interface over dynamic solidity limit of rock compression strength. In case of interaction of a cumulative jet with the rock the pressure on the interface affecting the cumulative jet from the rock side can be described as follows:

$$p = \frac{1}{2} p_c \left( V_c - V \right)^2 + o^- (1) \qquad (1)$$

Where $_c$ density of the cumulative jet material; $V_c$ travel velocity of a jet element in free flow; velocity of the interface movement "cumulative jet rock" (penetration speed); dynamic solidity of coating material CCC. The pressure acting from the cumulative jet side on the rock will be calculated as follows:

$$p = \frac{1}{2} \rho_{\Pi} v^2 + \left[ \sigma^- \right]_c^{\text{Д}} \qquad (2)$$

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**Corresponding Author:** Kaerbek Rafkatovich Argimbaev, National Mineral Resource University "University of Mines", 21 Line V.O., 2, 199106, St. Petersburg, Russia

where ρc rock density; $[\sigma]_{\text{ж}}^{\text{Д}}$ dynamic solidity limit of compression. Using the law of Bernoulli we can get the following equations:

$$\frac{1}{2}\rho_c\left(V_c - V\right)^2 - \frac{1}{2}\rho_{\text{П}} V^2 + \sigma^- \left[\sigma^-\right]_{\text{ж}}^{\text{Д}} = 0 \tag{3}$$

The solution to the equation (3) can be shown as:

$$V = V_c^2 \frac{\lambda}{\lambda^2 - 1}\left[\lambda - \sqrt{1 + \left(\lambda^2 - 1\right)\frac{2A}{p_c V_c}}\right], \tag{4}$$

Where:

$$\lambda^2 = \frac{\rho_c}{\rho_{\text{П}}}; A = \left[\sigma^-\right]_{\text{ж}}^{\text{Д}} - \sigma \tag{5}$$

The solution Eq. 4 analysis shows that the velocity of cumulative jet penetration into rock depends on the solidity of the mass to be shattered, cumulative jet and speed of the jet front side. During the flow under the influence of the velocity gradient the elongation of a cumulative jet occurs. Should the cumulative jet reach the ultimate elongation which is determined by its geometrical and kinetic parameters, it will separate into fragments.

The law of a full cumulative jet implementation is different from the law of implementing a separate fragment into the mass. This difference occurs due to the fact that the velocity of the fragment is constant throughout its length therefore during the process of implementation the fragment length doesn't grow but decreases on account of its consumption to form a crater in the rock mass. The velocity of a full cumulative jet is variable at its length and during the process of implementation it gets longer because there is a velocity gradient. The depth of a jet fragment implementation into the rock mass can be calculated as follows:

$$L = 1\left(\frac{V}{V_r - V}\right) \tag{6}$$

where, l-length of a jet fragment; V-velocity of implementing a jet element into the rock;-velocity of a jet element travel in free flow.

The solution Eq. 5 determines the depth of fragment penetration without taking into consideration its solidity. The material solidity of the fragment is determined by the travel law of that part of the fragment which is not directly connected with the rock and experiences some braking due to the fact that the fragment velocity differs from the initial penetration velocity. The law of a not implemented fragment part looks as follows:

$$\rho_c l_{1\,\frac{dv_c}{dt}=-\sigma} \tag{7}$$

where, length of a not implemented fragment part. With respect to the fragment braking to calculate the depth of implementation it is necessary to have a common equation solution Eq. 4-6 with the initial condition as follows:

$$1 = 1\big|_{t=o}; V_r = V_r\big|_{t=o}; V = V\big|_{t=o}; \frac{dv_c}{dt}\big|_{t=o} \tag{8}$$

When considering the process of the full cumulative jet implementation into the mass, the jet should be divided into N separate elements having constant velocity at full element length. Thus the total depth of L cumulative jet implementation will be the sum of depths of implementing each element:

$$L = \sum_{i=1}^{n} L_i \tag{9}$$

## RESULTS AND DISCUSSION

To confirm the presumption made above we carried out the X-ray filming of implementing cumulative jet created with respect to functioning CCC ($d_{\text{çàõ}}$= 6,75m) into a rock model 30 mm thick. The process of implementing a cumulative jet through 4,9c after starting CCC is seen on the X-ray photograph. The X-ray photograph (Fig.1) shows that the velocity of implementing is lower than the travel velocity of the cumulative jet in the air. Besides our experiments showed that the cumulative jet velocity reduces depending on the implementation depth and the cumulative jet itself becomes longer during the process of implementation.

As one can see in the above solution Eq. 5 the depth of implementing a cumulative jet element doesn't depend on the material of the rock mass and it will be bigger in case its length grows. In turn the length of the cumulative jet depends on the distance between the charge and mass. The longer this distance, the longer the cumulative jet is. However, it can't become longer and longer as there is a

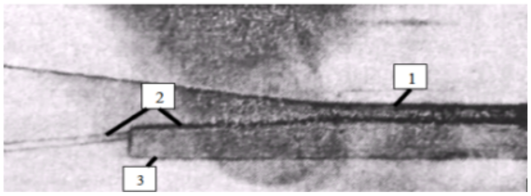

Fig. 1: X-ray photograph of the process to implement the cumulative jet into a rock plate (t = c): 1: CCC; 2: a cumulative jet; 3: a rock plate

Table 1. The size of an initial cavity depending on the focal distance

| Block material | Distance between CCC and the block, ($m.10^{-3}$) | Size of initial cavity made by a cumulative jet, ($m.10^{-3}$) |
|---|---|---|
| Marble | 0.0 | 5.0 |
| | 0.5 | 11.0 |
| | 10.0 | 8.0 |
| | 30.0 | 3.0 |
| Granite | 0.0 | 3.0 |
| | 0.5 | 6.0 |
| | 10.0 | 9.0 |
| | 30.0 | 2.0 |

limited length value ($l_{iõ}$) and after reaching this value the material will fall into fragments (Soldatov *et al*., 2014; Hu *et al* ., 2014). An effective influence of the fragmented cumulative jet on the rock will be significantly reduced due to dispersion of elements. The distance at which the jet is the most efficient is called focal.

In this studies (Orlenko, 2002; Lavrentjev, 1957), we can see that a focal distance is usually defined as a distance at which the cumulative jet falls into fragments. According to this definition the focal distance depends only on the properties of coating material (for example, coating material plasticity of a cumulative cavity).

When considering the interaction of CCC with the rocks on the first stage it was necessary to study the mechanism of implementing the cumulative jet and creation of an "initial" cavity (stress concentrator).

That was the reason to drill a blast hole in marble and granite blocks with dimensions 700x600x90. There were CCC in the holes in the form of a copper tube (ø>6,75 mm) filled with highly-explosive BB. On its side surface there was a hemicylindrical cumulative hole with radius 1,5mm.

Different values of the cumulative jet implementation depth, i.e., the length of initial cavities were achieved on account of the distance change between CCC and a rock block. The experiment results are shown in Table 1.

You can see in studies (Azharonok, *et al* ., 2008; Gromilov and Kinelovskii, 2003; Savenkov *et al.*, 2015) distance is usually a distance at which the cumulative jet falls into fragments. Accordingly the focal distance can be determined by only the properties of a cumulative hole coating material.

However the given experiment data concerning the depth of implementing the cumulative jet into rocks show that the mass material greatly affects the focal distance (Andrievskiy and Àvdeev, 2005). This can be explained by the fact that at the moment when a fragment of the cumulative jet affects the rock, there is a reflected shock wave in the latter which is directed to the rear side of the fragment giving it a negative speed. This leads to braking the subsequent fragment causing the reduction of efficiency to implement the cumulative jet into the rock (Golovatenko and Golovatenko, 2014). The diagram in Fig. 2 shows how the rock affects the cumulative jet.

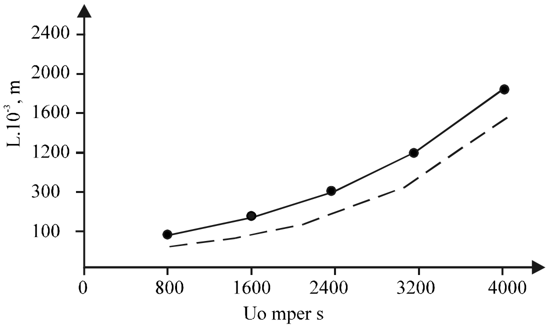

Fig. 2. The scheme of effect occurring between different cumulative jet fragments and the rock

Figure 2 shows the travel of two jet fragments following each other at intervals of $\theta_2$, $\theta_3$. At the moment $\theta_1$ the first fragment reaches the rock and the implementation of the fragment into the rock starts but the shock wave ae caused by the impact of the head fragment part with the rock reflects on the fragment itself. The path of implementing the fragment into the rock will go along ae, the rear side of this fragment brakes by means of the reflected shock wave and travels along the path bc, at the point c the rear side of the first fragment meets the head side of the second fragment. As a result of the impact a new shock wave occurs which accelerates the travel of the first fragment changing its path for ce.

As a result the first fragment makes a rock crater whose depth is $L_1$, the second fragment reflects the shock wave ââ which brakes its movement. The head side of the second fragment moves to meet the first along the path cf. At the moment of reaching the rock (point f) there is a reflected shock wave fg braking the travel of the rear part (path gh). As a consequence of this braking effect the total depth of penetration $L_0$ is smaller than the depth of penetration L which would be calculated without braking (implementation path ei)

The intensity of the shock wave and consequently its braking action is determined both by the impact velocity of the mass jet and by the material compression at the moment of impact (Latyshev, 2007).

The parameters of waves occurring at the moment of impact of the jet with the rock were determined according to the condition of balance on the pressure interface from the jet side and the mass ($P_x$). Thereby the velocity of the interface ($U_{ãõ}$) is calculated as follows:

$$U_{\text{rp}} = U_2 = U_0 - U_1 \tag{10}$$

where, $U_{rp}$ travel velocity on the pressure interface; $U_0$ velocity of the fragment head side; $U_1$ mass velocity of the reflected shock wave in the cumulative jet; $U_2$ mass velocity in the rock.

The values of mass velocities are determined by the pressure of the shock wave occurring at the moment of impact by initial and current values of material densities (Rumyantsev, 2015; Yan, 2007):

$$U_1 = \sqrt{P_1\left(\frac{1}{p_{oc}} - \frac{1}{p_c}\right)}; U_2 = \sqrt{P_2\left(\frac{1}{p} - \frac{1}{p}\right)}, \tag{11}$$

Where, $P_1$, $P_2$ – pressure in the front shock wave in the cumulative jet and the rock; $\text{ñ}_{\text{iñ}}$, $\text{ñ}_{\text{ñ}}$- initial and current density of the material of the cumulative jet; $\text{ñ}_{\text{ii}}$, $\text{ñ}_{\text{i}}$ – initial and current density of the rock material.

The pressure in the shock wave is determined by means of an equation of impact adiabat as follows:

$$\begin{cases} P_1 = p_{oc}D_cU_1 = p_{oc}U_1(C_{oc} + \lambda_cU_1), \\ P_2 = p_{on}D_nU_2 = p_{oc}U_0(C_{on} + \lambda_nU_2), \end{cases} \tag{12}$$

where $P_1$, $P_2$ – pressures in the front shock wave in the cumulative jet and the rock; $D_c$, $D_i$ – velocity of the shock wave in the jet and rock; $D_{\text{ic}}$, $D_{\text{ii}}$ ; $\text{ë}_{\text{ñ}}$ ,$\text{ë}_{\text{i}}$ – parameters of impact adiabat of the jet and rock material; $U_1$, $U_2$ – mass velocity of the shock wave in the jet and rock.

$$\sqrt{\frac{P\left[\sqrt{\frac{C^2_{oc}}{\lambda^2_{oc}} + \frac{P_\chi}{p_{oc}\lambda_c}} - \frac{C_{oc}}{2\lambda_c}\right]}{p_{oc}\left[\frac{C_{oc}}{2\lambda_c}(2\lambda_c - 1) + \sqrt{\frac{C^2_{oc}}{\lambda_c} + \frac{P_\chi}{p_{oc}\lambda}}\right]}} + \sqrt{\frac{p_\chi\left[\sqrt{\frac{C^2_{on}}{2\lambda^2_n} + \frac{p_x}{p_{on}\lambda_n}} - \frac{C_{on}}{2\lambda_n}\right]}{p_{on}\left[\frac{C_{on}}{2\lambda_n}(2\lambda - 1) + \sqrt{\frac{C^2_{on}}{\lambda^2_n} + \frac{P\lambda_n}{p_{on}\lambda_n}}\right]}} = U_0 \tag{13}$$

Using the law of Bernoulli about the equality of pressures on the interface we can get the following equation.

The equation was solved numerically by a method of iteration. Finally we got a mass velocity of the fragment shock wave at the moment of their impact with the rock blocks. The results of the calculation are shown in Fig. 3. Fig. 4 shows the calculation connections of the depth of implementing the cumulative jet into materials being investigated.

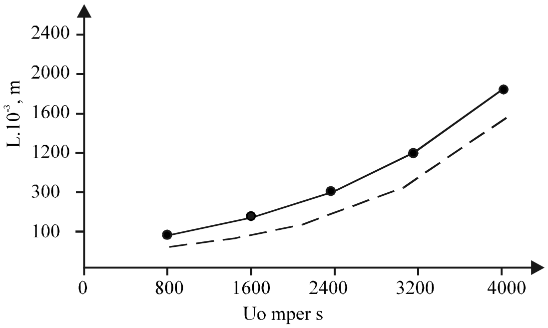

Fig. 3: Connection of the mass velocity in the reflected shock wave for the rear side of the jet ($U_1$) with the velocity of its front side ($U_0$). 1-granite; 2-marble

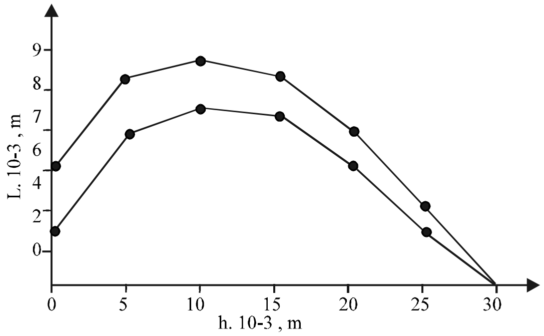

Fig. 4: Depth connection of implementing the cumulative jet with the distance to the mass; 1- marble; 2- granite

## CONCLUSION

The following conclusions can be drawn from the connections shown in fig. 3 and 4. The velocity of fragment braking increases when passing from marble to granite and consequently the depth of implementing the cumulative jet will reduce in a similar way.

The focal distance for the rocks being investigated is different and increases from marble to granite. The values of focal distance are lower than the distance at which the cumulative jet falls into fragments. Thus, we can confirm the fact that the mass material affects the focal distance for cumulative charges.

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