MODELING IMPACT FRACTURE OF ROCK BY HYDRAULIC HAMMER PICK WITH REGARD TO ITS BLUNTNESS

Introduction

Mineral mining industry is an important budget-generating sector in economies of many countries, including Russia [1]. It is impossible to increase the budget without advanced methods of mining at hand. Extraction of minerals is a complex process implemented using various methods and machines [2–6]. Efficiency of blasting as the most widely used method in mineral mining largely depends on drilling equipment and tools [4, 7]. On the other hand, some operations need that only the impact method is used (fracture of oversizes, removal of spalling, etc.). The impact tools that immediately interact with rocks suffer from fast wear. Such deterioration of the tools reduces productivity and raises expenses connected with purchase of new tools. Extensive studies are currently undertaken to find ways of extending service life of impact tools through re-design, use of new materials or application of innovative machining techniques [8–17].

The theoretical framework of the impact destruction of rocks is described by both Russian and foreign scientists [18–33]. Penetration of an impact tool in rocks is modeled mathematically, and the energy input of rock fracture and the impact machine capacity are estimated [34–36]. In the meanwhile, the influence of the impact tool blunting on the impact efficiency lacks proper attention. This article is an attempt to fill the gap.

The mathematical model of impact tool penetration in rocks and rock-bearing composites uses research findings of Professor Sokolinsky [37].

Modeling was implemented as a case-study of hydraulic hammering of granite ($q_{\text{com}} \sim 200$ MPa). The rock-breaking tool of a hydraulic breaker is the pick. Specifications of the hydrobreaker are as follows:

<table>
<thead>
<tr>
<th>Model</th>
<th>JCB HM380</th>
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<tbody>
<tr>
<td>Range</td>
<td>Medium</td>
</tr>
<tr>
<td>Rock breaker</td>
<td>Pick</td>
</tr>
<tr>
<td>Impact energy $A_p$, J</td>
<td>981</td>
</tr>
<tr>
<td>Impact frequency $v$, $s^{-1}$</td>
<td>5–10</td>
</tr>
<tr>
<td>Pick velocity in blow, $v_p$, m/s</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The impacting assembly of the hydraulic breaker consists of a piston (with its face shaped as a hemisphere with radius $R_p = 0.5$ m) and a cylindrical pick with an edge in the form of a blunted cone (mass $M_{\text{pick}} = 25$ kg; length $L_{\text{pick}} = 800$ mm; cylindrical part radius $R_{\text{cyl}} = 37.5$ mm; cone height—$100$ mm; cone angle—$30\degree$; the cone blunt is a hemisphere).

Inspection of a pick after destruction of a granite oversize shows that the cone edge of the pick changes its shape because of wear into a hemisphere with a radius $r_{\text{sp}} = 13$ mm (onset of hemisphere formation). As wear grows, the pick length shortens and the cone bluntness radius increases up to $r_{\text{sp}} = 37.5$ mm. The tool bluntness $S_{\text{tool}}$ is given by:

$$S_{\text{tool}} = r_{\text{sp}}/R_{\text{cyl}}$$  \hspace{1cm} (1)

where $r_{\text{sp}}$ is the cone sphere radius at the moment of measurement, mm; $R_{\text{cyl}}$ is the cylinder part radius of the pick, mm. At the moment of initiation of a hemisphere, $S_{\text{tool}} = 0.35$ (at $r_{\text{sp}} = 13$ mm), and in the critical condition of the tool, $S_{\text{tool}} = 1$ (at $r_{\text{sp}} = 37.5$ mm).

The contact stiffness analysis on the basis of [37] used the factor of energy transmission from the breaker to rock via the pick:

$$\varepsilon = 1/(1 + e_i/e_o),$$

where $e_i$ is the pick–rock contact stiffness, N/m$^2$; $e_o$ is the piston–pick contact stiffness, N/m$^2$:

$$e_i = \frac{4\sqrt{\varepsilon}}{3\left(1-\frac{1}{E_{\text{tool}}}+1-\frac{1}{E_{\text{rock}}}ight)}$$  \hspace{1cm} (3)

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is the rock elasticity, GPa (50 GPa); \( \varepsilon_{\text{tool}} \) is the tool material elasticity, GPa (200 GPa); \( \varepsilon_{p} \) is the piston material elasticity, GPa (50 GPa); \( \mu_{\text{rock}} \) is Poisson’s ratio of rock (0.2); \( \mu_{\text{tool}} \) is Poisson’s ratio of the tool material (0.3).

The calculated value of the energy transmission factor at different tool bluntness \( (r_{e}) \) approaches 1 (0.9–0.94). This enables withdrawal of the piston–hammer intermediate system from the calculation to analyze the two-component pick–broken rock system only. According to Sokolinsky’s theory [37], another condition for this two-component system is the absence of wave processes in the breaker. This condition is fulfilled when the concussion duration exceeds or equals three periods of free vibrations of a colliding body. In case of the short pick of JCB HM380 breaker, the concussion duration is 1 ms at the free vibration period of 0.3 ms.

On the basis of [37], the breaking tool penetration in rocks has three stages:

1. Rock exhibits elastic properties until reaching a critical stress at the contact with the tool. With increasing stress, an explosion-like failure of rock takes place at the contact.
2. The tool penetrates deeper, overcoming the failure core and squeezing broken rock chips out. The rest of broken rocks is pressed at bottomhole.
3. The tool is pushed back under the action of residual elasticity of the pressed broken rock chips.

The rock resistance \( F \) depends on the tool penetration depth \( h \) (rock deformation) and, according to [37], in case of a hemisphere contact area, is nonlinear and composed of three loads: \( F_{1} \)—elastic deformation at contact; \( F_{2} \)—tool penetration in broken rock; \( F_{3} \)—tool kick. Each load has its own stiffness.

It follows from [37] that the maximum resistance \( F_{\text{max}} \), penetration \( a_{\text{pen}} \), impact time \( t_{\text{max}} \) and the maximum stress \( a_{\text{cr}} \) at the contact under such loading are given by:

\[
F_{\text{max}} = F_{\text{rock}} + \varepsilon_{p}(a_{\text{max}} - a_{\text{rock}})^{3/2},
\]

\[
F_{\text{rock}} = \frac{9}{2} \left( \frac{1 - \mu_{\text{tool}}^{2}}{E_{\text{tool}}} + \frac{1 - \mu_{\text{rock}}^{2}}{E_{\text{rock}}} \right) r_{\text{ipp}}^{2} \phi_{\text{cr}}
\]

where \( r_{\text{ipp}} \) is the fracture force at the contact; \( a_{\text{rock}} \) is the elastic deformation of rock;

\[
a_{\text{rock}} = \left( F_{\text{rock}}/\varepsilon_{p} \right)^{2/3},
\]

where \( \phi_{\text{cr}} \) is the estimated rock breakage efficiency. This value was found from the equation below:

\[
\phi_{\text{cr}} = \frac{a_{\text{max}}}{a_{\text{rock}}},
\]

where \( a_{\text{max}} \) is the tool mass; \( T_{c} \) is the hardness factor.

The change in the value of \( r_{e} \) in the expressions of the stiffnesses \( \varepsilon_{1} \) and \( \varepsilon_{2} \) allows assessing the influence of the tool bluntness on the impact efficiency.

**Unit blow calculations**

Using Eqs. (5)–(12), the tool bluntness \( S_{\text{tool}} \) is related with the maximum resistance \( F_{\text{max}} \), penetration \( a_{\text{pen}} \), impact time \( t_{\text{max}} \) and the maximum stress \( a_{\text{cr}} \) at the contact.

The modeling assumed the critical stress \( a_{\text{cr}} \) of granite as its dynamic hardness \( a_{\text{cr}} = 1300 \text{ MPa} \) [38]. That value was selected to comply with the conclusions made in [39] that the strength characteristics of most rocks increase in transition from static to dynamic loading. The stiffness values were selected in conformity with [39]: \( \varepsilon_{2} = 0.15 \varepsilon_{1} \) and \( \varepsilon_{2} = \varepsilon_{1} \).

Nearly half kinetic energy \( \varepsilon_{3} \) is spent for destruction of rocks \( (\varepsilon_{\text{rock}}) \), the rest of energy goes to heating of rocks and to elastic straining of the tool.

The relationships plotted after solution of (5)–(12) (Fig. 1) show that at the constant momentum, the maximum rock resistance to the tool penetration (curve 1) monotonously grows as the tool gets blunt. The same holds true for the blow time (curve 3). At the same time, the penetration depth value decreases (curve 2). The contact stress in granite remains almost unaltered (around 686 MPa).

**Multiple impact calculations**

The shearing tests of rocks using JCB HM380 hydraulic breaker in an open pit mine show that rock is fractured...
after a series of nearly 30 blows at the same point. And the penetration depth of the tool decreases with every next blow. This phenomenon is taken into account in the model.

The increasing friction increases the rock resistance \( F_{\text{max}} \) to penetration per blow in proportion to the penetration depth \( a_{\text{pen}} \), which results in the decreasing \( a_{\text{pen}} \) under each subsequent blow. The resultant total loading characteristic is depicted in Fig. 2.

Figures 3 and 4 correlate the maximum resistance \( F_{\text{max}} \) and maximum blow time \( t_{\text{max}} \) in each cycle, and the total penetration depth \( \Sigma a_{\text{pen}} \) and time \( \Sigma t_{\text{blow}} \) per cycle at different bluntness of the tool.

Resistance of rock to pick penetration grows in each blow in the cycle (see Fig. 3), and the time of blow reduces. By the 30th blow, the blow time is two times less than in the first blow. The increase in the tool bluntness from 0.35 to 1.0 (see Fig. 4) reduces the total penetration depth \( \Sigma a_{\text{pen}} \) in rock per cycle by 28% and the total maximum time \( \Sigma t_{\text{max}} \) shortens by 20%.

**Experimental validation of calculation results**

The data of fracture testing of concrete (\( \sigma_{\text{con}} \sim 50 \) MPa) were compared with the calculations. The measurements were taken in the step-frame analysis of the video film of the hydrobreaker operation. The penetration depth was determined from the displacement of the check point on the tool (mark 0, Fig. 5) relative to recorded marks (1, 2 and 3, Fig. 5) In this fashion, the penetration depth \( a_{\text{pen}} \) of the tool in rock was determined after each blow in the cycle together with the total penetration depth after 30 blows (Fig. 6).

The analytical and experimental data agree, which proves applicability of the mathematical model in further research.

**Conclusions**

As a result of the implemented research, the mathematical model of the breaking tool penetration in rock is built. It is found that the critical bluntness of the tool pick increases the rock penetration resistance up to 2 times at the decrease in the penetration depth by 28% and in the maximum blow time by 20%. The experimental data agree with the calculated results.

**References**


