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

Destruction of rocks and artificial composites is carried out in various ways. One of the most common methods is the impact fracture. The conical pick of JCB HM380 hydraulic breaker was used as the impact tool. The experimental study of rock fracture was carried out on an artificial composite—concrete. The depth of penetration of the pick into concrete was used as the test parameter. The model was based on the model of Professor V. B. Sokolinsky. The model developed in this work takes into account the degree of bluntness of the tool in single and multiple impact. The system was considered as a two-component system due to the high stiffness of the pick—granite contact (as against the hammer piston—pick stiffness). The wave processes in the pick were disregarded because of the small length of the pick. The pick penetration depth in rocks was calculated theoretically, using the developed mathematical model, at each impact of the pick, and then was compared with the experimental data. The fracture tests also used JCB HM380 breaker and concrete. The penetration depth was determined from the step-frame analysis of video filming of the process. It is found that the pick blunting causes a monotonic increase in the rock resistance to the pick penetration, both in single and multiple impact, while the depth of the tool penetration and the blow time decrease (as compared with the initial state of the tool, by 28% and 20%, respectively).

Keywords: *hydraulic hammer, pick, bluntness, penetration, granite, mathematical model, impact parameters*
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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 (σ_{com} ~200 MPa). The rock-breaking tool of a hydraulic breaker is the pick. Specifications of the hydrobreaker are as follows:

Model	*JCB HM380*
Range	*Medium*
Rock breaker	*Pick*
Impact energy A_0, J	*981*
Impact frequency ν, s^{-1}	*5–10*
Pick velocity in blow, v_0, m/s	*6.3*

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_{pick} = 25 kg; length L_{pick} = 800 mm; cylindrical part radius R_{cyl} = 37.5 mm; cone height—100 mm; cone angle—30°; 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_{sp0} = 13 mm (onset of hemisphere formation). As wear grows, the pick length shortens and the cone bluntness radius increases up to r_{cr} = 37.5 mm. The tool bluntness S_{tool} is given by:

$$S_{tool} = r_{sp}/R_{cyl}, \quad (1)$$

where r_{sp} is the cone sphere radius at the moment of measurement, mm; R_{cyl} is the cylinder part radius of the pick, mm. At the moment of initiation of a hemisphere, S_{tool0} = 0.35 (at r_{sp0} = = 13 mm), and in the critical condition of the tool, S_{toolcr} = 1 (at r_{cr} = 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:

$$\varepsilon = 1/(1 + e_1/e_0),$$

where e_1 is the pick–rock contact stiffness, N/m$^{3/2}$; e_0 is the piston–pick contact stiffness, N/m$^{3/2}$:

$$e_1 = \frac{4\sqrt{r_c}}{3\left(\frac{1-\mu_{tool}^2}{E_{tool}} + \frac{1-\mu_{tool}^2}{E_{rock}}\right)}, \quad (3)$$

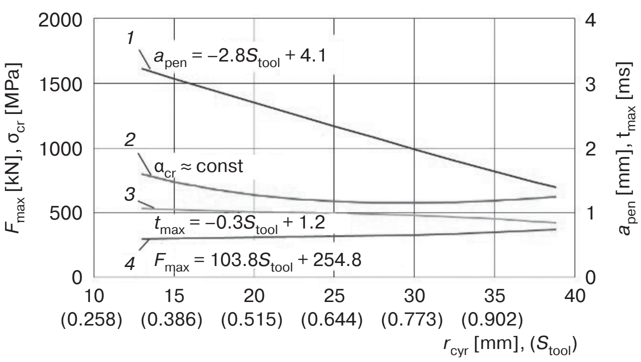

Fig. 1. Relationship of a_{pen} (*1*), σ_{cr} (*2*), t_{max} (*3*), F_{max} (*4*) and pick bluntness during impact penetration of JCB HM380 breaker in granite

$$e_0 = \frac{2E_p\sqrt{R_p}}{3}, \quad (4)$$

where E_{rock} is the rock elasticity, GPa (50 GPa); E_{tool} is the tool material elasticity, GPa (200 GPa); E_p is the piston material elasticity, GPa (50 GPa); μ_{rock} is Poisson's ratio of rock (0.2); μ_{tool} is Poisson's ratio of the tool material (0.3).

The calculated value of the energy transmission factor at different tool bluntness (r_{sp}) 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_{max}, penetration a_{pen}, impact time t_{max} and the maximum stress σ_{cr} at the contact under such loading are given by:

$$F_{max} = F_{rock} + e_2(a_{max} - a_{rock})^{3/2}, \quad (5)$$

$$F_{rock} = \frac{9\pi^3}{2}\left(\frac{1-\mu_{tool}^2}{E_{tool}} + \frac{1-\mu_{rock}^2}{E_{rock}}\right)^2 r_{sph}^2\sigma_{cr}^3, \quad (6)$$

where F_{rock} is the fracture force at the contact; a_{rock} is the elastic deformation of rock;

$$a_{rock} = (F_{rock}/e_1)^{2/3}, \quad (7)$$

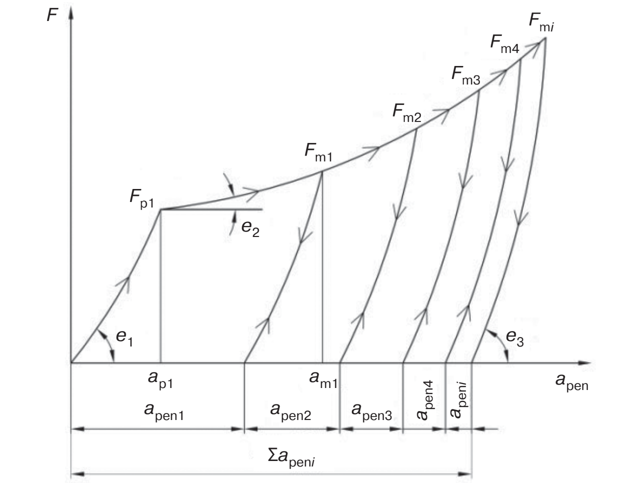

Fig. 2. Shape of loading characteristic in multiple impact calculation

$$e_1 = \frac{4\sqrt{r_{sph}}}{3\left(\frac{1-\mu_{tool}^2}{E_{tool}} + \frac{1-\mu_{rock}^2}{E_{rock}}\right)}, \quad (8)$$

$$a_{pen} = a_{max} - (F_{max}/e_3)^{2/3}, \quad (9)$$

where a_{max} is found from the equation below:

$$\frac{2}{5}e_1 e_{rock}^{5/2} + F_{rock}(a_{max} - a_{rock}) + \frac{2}{5}e_2(a_{max} - a_{rock})^{5/2} = A_I, \quad (10)$$

$$t_{max} = mv_0/F_{max}, \quad (11)$$

$$\sigma_{cr} = F_{max}/f_h, \quad (12)$$

where m is the tool mass; f_h is the hardness factor.

The change in the value of r_{sp} in the expressions of the stiffnesses e_1 and e_2 allows assessing the influence of the tool bluntness on the impact efficiency.

Unit blow calculations

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

The modeling assumed the critical stress σ_{cr} of granite as its dynamic hardness σ_d = 1300 MPa [38]. That value was selected to comply with the conclusions made in [39] that the strength characteristics of most rocks increased in transition from static to dynamic loading. The stiffness values were selected in conformity with [39]: $e_2 = 0.15e_1$ and $e_3 = e_1$.

Nearly half kinetic energy E_0 is spent for destruction of rocks (E_{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

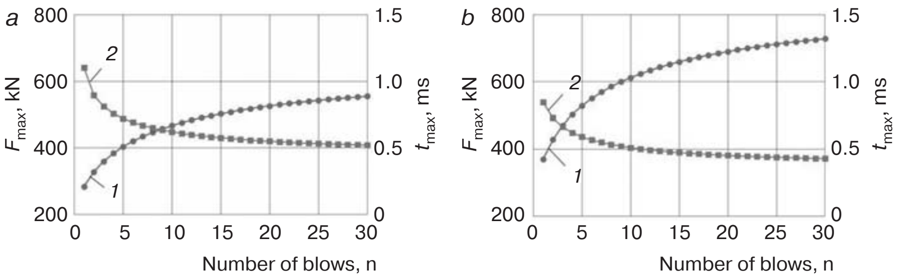

Fig. 3. Maximum penetration time (*1*) and granite penetration resistance (*2*) versus number of blows per cycle at bluntness: *a*—k_{b0} = 0.35 (initial condition); *b*—k_{bcr} = 1.0 (total worn-out tool)

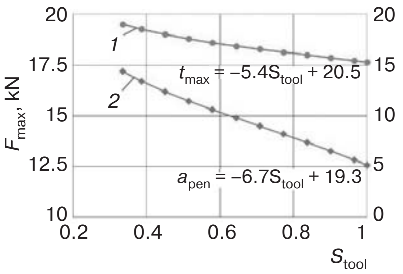

Fig. 4. Total maximum time Σt_{maxi} of blow in cycle of 30 blows (*1*) and total penetration depth Σa_{peni} in granite (*2*) versus tool bluntness

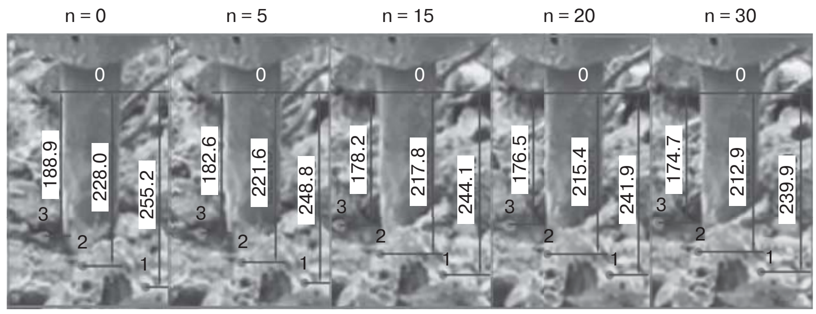

Fig. 5. Step-frame analysis of video film of tool penetration in concrete (*n*—number of blows)

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_{maxi} to penetration per blow in proportion to the penetration depth a_{peni}, which results in the decreasing a_{peni} under each subsequent blow. The resultant total loading characteristic is depicted in **Fig. 2**.

Figures 3 and **4** correlate the maximum resistance F_{maxi} and maximum blow time t_{maxi} in each cycle, and the total penetration depth Σa_{peni} and time Σt_{mi} 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 30rd 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 Σa_{peni} in rock per cycle by 28% and the total maximum time Σt_{maxi} shortens by 20%.

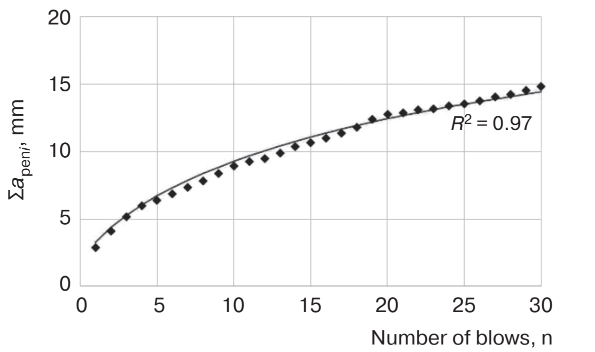

Fig. 6. Calculation (line) and experiment (♦) depths of tool penetration in concrete versus blow number

Experimental validation of calculation results

The data of fracture testing of concrete (σ_{com} ~ 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_{peni} 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.

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