IMPACT FRACTURE OF ROCK MATERIALS DUE TO PERCUSSIVE DRILLING ACTION

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Summary A theoretical model describing impact fracture of rocks caused by percussive drilling is presented. The process is modeled using particle dynamics (molecular dynamics) approach where a special interaction law for brittle materials is formulated. Relations between the microscopic quantities of the model and the macroscopic mechanical properties have been established. The material fracture and cracks formation under the periodic set of inserts are investigated.

INTRODUCTION

Percussive drilling is proved to be superior when compared to a convention rotary drilling especially in the case of hard and brittle rock materials [1]. The impacts generated by the percussive drilling action produce fracture in the brittle material, which allows increasing drastically the penetration rate. Rotation of the tool for the percussive drilling is mostly responsible for the debris removal, while the main progression is caused by the impact fracture. That is why to predict and optimize the behavior of the drilling tool it is essential to study thoroughly the impact interaction between the tool and the processed material. In the previous work the low-dimensional models where developed, allowing to describe the specifics of the percussive drilling, in particular the optimum ratio between the static and dynamic components of the load were predicted [2, 3]. However, these models describing the material behavior are crude, limiting its properties to only several effective parameters. To understand better the fracture processes accompanying the percussive drilling more detailed study of the fracture scenario is needed. This investigation can be based on the particle dynamics model, which gives advantages comparing to the continuum approaches when the assumption of the material continuity fails [4, 5].

MODELLING THE IMPACT FRACTURE

Let us assume that the drillbit surface is covered by a set of inserts, which interact with the material surface. The interaction of the insert with the rock half-space is depicted in Fig.1 a, where the model state just after the impact is shown. The upper rectangle simulates the insert, the lower one — the rock material. In the horizontal direction periodic boundary conditions are used to mimic the periodic set of inserts. Initially the rock has zero velocity, the tool has constant velocity directed towards the rock. For the parameters estimation this problem can be reduced to 1D continuum model, which shows that the main dimensionless parameters to take into account are

$$\tilde{v} \overset{\text{def}}{=} \frac{v_1}{v_2}, \qquad \tilde{\rho} \overset{\text{def}}{=} \frac{\rho_1}{\rho_2}; \qquad v_2^2 \overset{\text{def}}{=} \frac{C_{1111}}{\rho_2} = \frac{1-\nu}{(1+\nu)(1-2\nu)}\,\frac{E}{\rho_2}; \tag{1}$$

where v_1 is the tool velocity, v_2 is the velocity of longitudinal waves in the rock material, ρ_1 is the tool density, ρ_2 is the material density; C_{1111} is the longitudinal stiffness, E is the Young modulus, and ν is the Poisson ratio of the rock material. Then the shock wave propagation can be described by the equation (below H is the Heaviside step function)

$$\varepsilon(\tau,\tilde{x}) = -\tilde{v}e^{-(\tau-\tilde{x})/\tilde{\rho}}H(\tau-\tilde{x}); \qquad \tau \overset{\text{def}}{=} \frac{t}{w/v_2}, \qquad \tilde{x} \overset{\text{def}}{=} \frac{x}{w}; \tag{2}$$

where ε is the longitudinal deformation, x is the longitudinal coordinate, w is the average distance between the inserts.

Particle dynamics technique

The impact dynamics is simulated on the base of conventual molecular-dynamics technique [6], where the both materials (the insert and the rock) are formed by close-packed crystal lattices of particles. The motion of the particles is obtained through integration of the Newtonian equations of motions with the prescribed interaction forces:

$$F_1(r) = \left[\begin{array}{ll} F(r), & 0 < r \le b; \\ k(r)\,F(r), & b < r \le a_{\text{cut}}; \end{array}\right. \qquad F(r) = \frac{12D}{a}\left[\left(\frac{a}{r}\right)^{13} - \left(\frac{a}{r}\right)^{7}\right], \qquad b \overset{\text{def}}{=} \sqrt[6]{\frac{13}{7}}\,a \approx 1.11a; \tag{3}$$

where $F(r)$ is the force corresponding to the Lennard-Jones potential with the equilibrium distance a and bond energy D; quantity b is the brake distance for the Lennard-Jones interaction, $k(r)$ is the shape function

$$k_1(r) \overset{\text{def}}{=} (1+\alpha)\left(1 - \left(1 + \sqrt{\frac{\alpha}{1+\alpha}}\right)\left(\frac{r^2-b^2}{a_{\text{cut}}^2-b^2}\right)^2\right)^2 - \alpha, \tag{4}$$

where α is a positive parameter, defining brittleness of the material, $a_{\text{cut}} > b$ is the cut-off distance for the interaction. Increase of α results in the repulsion appearing in the vicinity of the cut-off distance. This produces potential barrier for joining two particles, which where separated due to the impact fracture.

The stiffness of the interparticle force is given by the expression $C \stackrel{\text{def}}{=} -F'(a) = 72D/a^2$. If we consider triangular lattice in 2D, then the elastic moduli of the corresponding material are $E_2 = 2C/\sqrt{3}$, $\nu_2 = 1/3$, where E_2 stands for the 2D Young modulus, ν_2 for the Poisson ratio. The elastic moduli E and ν for the corresponding 3D material (using the 2D strain assumption), can be expressed as

$$E = \frac{15\sqrt{2}}{16}\frac{C}{a} = \frac{135\sqrt{2}}{2}\frac{D}{a^3}, \qquad \nu = \frac{1}{4}; \qquad a = \sqrt{\frac{2S}{\sqrt{3}NS_0}}; \tag{5}$$

where S is considered cross-section area of the entire specimen, S_0 is the area occupied by a single particle, N is number of particles in the model. Formulae (5) allow obtaining potential parameters D and a from the macroscopic parameters of the system. The obtained value for the Poisson ratio is about the upper limit of the Poisson value for the dense rocks. In the frames of the current model the Poisson ratio can not be adjusted, but this is unlikely to produce big errors in computations, considering that the experimental data for the rocks is very irregular. In the current simulation the computational parameters are taken to obtain the computational rock material properties close to crystalline quartz, the indenter material is chosen to be 5 times harder then the rock material.

Simulation results

The sequential stages of the impact process are shown in Fig.1a–d, where propagation of the shock wave can be observed ($T \stackrel{\text{def}}{=} w/v_2$). Colors show distribution of the stress intensity $\sigma \stackrel{\text{def}}{=} \sqrt{\frac{1}{2}(\sigma_1 - \sigma_2)^2 + 2\tau_{12}^2}$, where σ_1 and σ_2 are normal stresses in the horizontal and vertical directions, τ_{12} is the corresponding shear stress. The color scale from blue to red corresponds to the stress scale from zero to the maximum value obtained in the experiment. Fig.1e shows the final stage of the impact fracture formation in the vicinity of the inserts. The simulation takes advantage of the model periodicity and this picture shows three periods in the horizontal direction. Cracks formed due to the impacts are well visible.

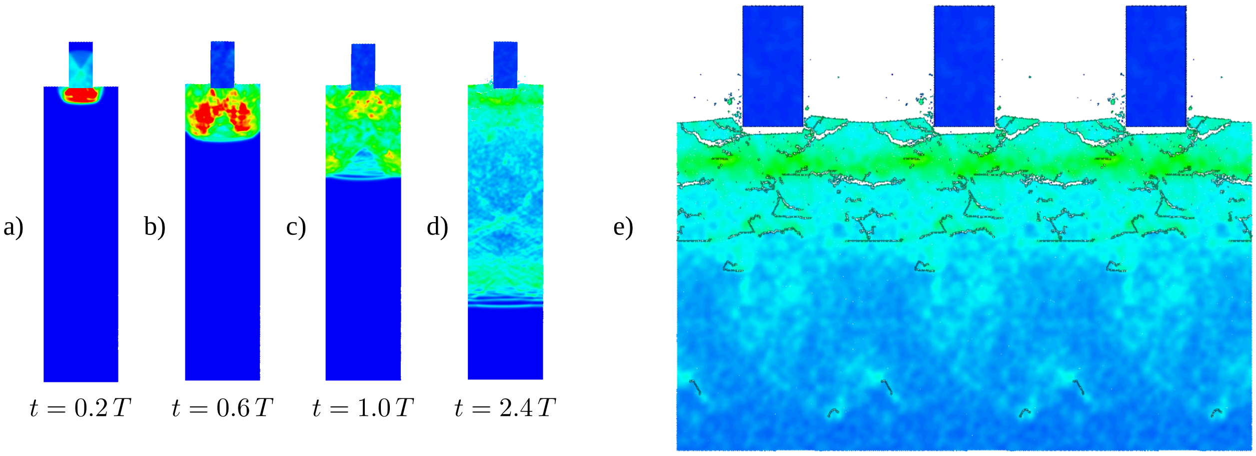

Fig.1. Simulation results: a)–d) shock wave propagation (10^4 particles); e) impact fracture in the specimen ($2 \cdot 10^5$ particles).

CONCLUSIONS

The study shows that the impact fracture locates mainly in the areas under inserts and between them, which is due to the shock wave interactions. A comparison between 2D particle dynamics and 1D continuum models shows a good agreement at the distances from the impact area, which are greater than the average distance between inserts. The cracks distribution and their orientation differ significantly from the quasistatic computations [7] and correlate well with the known experimental impact tests [8], and this confirms the dynamic nature of the considered process.

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