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Numerical and experimental study of percussive drilling with a triple-button bit on Kuru granite

Timo Saksala [a,*], Dmitri Gomon [b], Mikko Hokka [b], Veli-Tapani Kuokkala [b]

[a] *Department of Mechanical Engineering and Industrial Systems, Tampere University of Technology, P.O. Box 589, FI-33101 Tampere, Finland*
[b] *Department of Materials Science, Tampere University of Technology, P.O. Box 589, FI-33101 Tampere, Finland*

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A B S T R A C T

This paper deals with numerical and experimental research of percussive drilling. A finite element based modelling approach, developed earlier by the authors, was employed in the simulation of the dynamic bit-rock interaction process. The rock fracture in this approach was modelled with a damage-viscoplasticity model accounting for the main fracture types in the bit-rock interaction as well as the strain-rate effects. In the experimental part of the work, dynamic indentation tests were carried out on Kuru granite using a special triple-button drill bit where the buttons were inserted at the vertices of an equilateral triangle. The purpose of these experiments was to provide data on the fracture of the hard rock under percussive drilling action and to find the (experimental setup specific) striker impact velocity that leads to lateral chipping, i.e. material removal of rock between the adjacent bit-buttons. Despite the statistical nature of rock behaviour, which lead to the material removal at several striker impact velocities, these experiments provide a suitable validation problem for codes designed for numerical modelling of percussive drilling. The present modelling technique reproduced the experimental data with good accuracy in tests where the stress wave amplitude in the drill rod was up to 200 MPa. This stress level is seldom exceeded practical rock drilling. The simulation results deviated from the experimental results in the experiments with higher stress amplitude, which is probably due to the continuum assumption of the present modelling approach.

1. Introduction

Rock drilling has been widely used in, for example, open pit mines, quarries, and construction sites for many decades. A sound understanding of the bit induced fracture mechanisms is of great importance especially in the drill bit design. In percussive drilling, which is probably the most widely used drilling technique with hard rocks, an impact induced stress wave travels through the drill rod and forces the hard metal inserts at the drill bit to penetrate into the rock. This penetration causes material removal through crushing of the rock immediately beneath the buttons. Most of the energy available for the rock breakage is consumed in this crushing. However, the most important fracture mechanism concerning material removal with multiple-button bits is the coalescence of the side cracks (lateral chipping) induced by the interaction of adjacent buttons. This lateral chipping fracture should therefore be investigated also by numerical modelling. More information on rock fragmentation mechanisms due to drill bits can be found in the reviews by, e.g., Mishnaevsky [1], Liu [2] and Liu et al. [3].

Chiang and Elias [4] studied the energy transmission to the rock, the bit–rock interaction, and the process of rock fragmentation using a failure model similar to the orthotropic damage concept where the failure is indicated by the Mohr-Coulomb criterion in compression and the principal stress criterion in tension. The work by Zhu et al. [5] on 3D FE modelling of air hammer drilling uses the Mohr-Coulomb plasticity model with tensile cut-off to account for the rock failure in the dynamic simulation of a full-scale drill bit-rock interaction. Bu et al. [6] simulated pneumatic DTH hammer percussive drilling using LS-DYNA software. The material model used in their simulations was the Johnson-Holmquist concrete model with an equation of state for hydrostatic behaviour of rock. Finally, Saadati et al. [7] combined the Denoual-Forquin-Hild

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* Corresponding author. Tel.: +358 401893272; fax: +358 331152307.
E-mail addresses: timo.saksala@tut.fi (T. Saksala), dmitri.gomon@tut.fi (D. Gomon), mikko.hokka@tut.fi (M. Hokka), veli-tapani.kuokkala@tut.fi (V.-T. Kuokkala).

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fragmentation model with the Krieg-Swenson-Taylor plasticity model to describe the behaviour of granite in the bit-rock interaction. They validated the combined model by simulating the Edge-On-Impact experiment at different velocities. This test differs, however, considerably from the bit-rock interaction in percussive drilling by nature (boundary conditions). Therefore, the experiments carried out in the work presented in this paper are more relevant to percussive drilling.

This paper continues the work presented by the authors in Refs. [8–11]. A numerical method including a damage-viscoplastic material model for rock and an efficient scheme for modelling contact constraints were presented for low-velocity impact simulation in Ref. [8]. This method was then modified and applied in the simulations of dynamic bit-rock interaction in axisymmetric conditions [9]. The bit-rock interaction with a multiple-button bit is, however, not an axisymmetric problem, and even the rock material itself cannot be assumed axisymmetric due to its heterogeneity. Therefore, the method was extended to genuine 3D setting in Ref. [10]. The rock heterogeneity was accounted for at the mesoscopic (finite element) level statistically assuming the mechanical properties to be Weibull-distributed. Finally, an attempt to validate the numerical method based on dynamic indentation experiments on Kuru granite was made in Ref. [11]. The agreement between the model prediction and the experiments was quite good in the single-button case, but the experiments with a triple-button bit were not successful due to the impedance mismatch between the massive bit (in which the buttons were inserted) and the relatively thin drill rod used in the experiments. In this paper, the deficiencies of the previous experiments are mended by using a drill rod of uniform thickness with the buttons inserted directly to the end of the rod. The percussive drilling action, i.e. dynamic indentation at different impact velocities, was studied experimentally and numerically. The purpose of the experiments was to provide data on hard rock fracture induced by dynamic indentation using a triple-button indenter. More importantly, the experiments were carried out to find the critical impact velocity which leads to lateral chipping, i.e. material removal of rock between the adjacent bit-buttons. Determination of this critical velocity, despite being experimental setup specific, provides a good validation problem for the numerical codes designed to model the percussive rock drilling.

The outline of this paper is as follows. First, the theory of the simulation method is briefly sketched in Section 2. Then, the experimental setup is explained and some representative results on drill bit induced fracture patterns at different striker velocities are presented in Section 3. In the numerical examples (Section 4), the experiments are simulated with the present simulation method. Finally, the work is briefly summarized and some conclusions are drawn along with the assessment of model strengths and weaknesses.

2. The simulation method

The theory of the applied simulation method, including the constitutive model for rock and the bit-rock interaction model, is briefly presented in this section for the convenience of the reader. For more details, see original papers [8–11].

2.1. Constitutive description of rock

The constitutive model is based on the viscoplastic consistency model by Wang et al. [12] and an isotropic damage concept. The stress states leading to viscoplasticity and damage are indicated by the Drucker–Prager (DP) yield function with the Modified Rankine (MR) criterion and a parabolic cap surface as tension and compression cut-offs, respectively:

$$
\begin{aligned}
f_{\mathrm{DP}}(\boldsymbol{\sigma},\kappa_{\mathrm{DP}},\dot{\kappa}_{\mathrm{DP}}) &= \sqrt{J_2}+\alpha_{\mathrm{DP}}I_1-k_{\mathrm{DP}}c(\kappa_{\mathrm{DP}},\dot{\kappa}_{\mathrm{DP}})\\
f_{\mathrm{MR}}(\boldsymbol{\sigma},\kappa_{\mathrm{MR}},\dot{\kappa}_{\mathrm{MR}}) &= \sqrt{\sum_{i=1}^{3}\langle\sigma_i\rangle^2}-f_{\mathrm{t}}(\kappa_{\mathrm{MR}},\dot{\kappa}_{\mathrm{MR}})\\
f_{\mathrm{Cap}}(\boldsymbol{\sigma},c,p_{\mathrm{P}}) &= \sqrt{J_2}-C_1(c,p_{\mathrm{P}})I_1^2-C_2(c,p_{\mathrm{P}})I_1-C_3(c,p_{\mathrm{P}})
\end{aligned}
\qquad (1)
$$

where I_1 and J_2 are the invariants of the stress tensor $\boldsymbol{\sigma}$, σ_i is the principal stress, c, f_{t} are the cohesion and the tensile strength of the material, and $\kappa_{\mathrm{MR}}, \kappa_{\mathrm{DP}}$ and $\dot{\kappa}_{\mathrm{MR}}, \dot{\kappa}_{\mathrm{DP}}$ are the internal variables and their rates in tension and compression, respectively. Moreover, McAuley brackets have been used in Equation (1) and C_1, C_2 and C_3 are coefficients (functions of c and p_{P}) that define the location of the cap in relation to the DP cone. The Drucker–Prager parameters in Equation (1) are expressed as a function of the friction angle φ and defined so that the uniaxial compressive strength is matched: $\alpha_{\mathrm{DP}} = 2\sin\varphi/(3-\sin\varphi)$ and $k_{\mathrm{DP}} = 6\cos\varphi/(3-\sin\varphi)$. A plastic potential of form $g_{\mathrm{DP}} = \sqrt{J_2}+\beta_{\mathrm{DP}}I_1-C$ (where C is a constant and β_{DP} depends on dilatation angle ψ instead of the friction angle) is chosen in order to account for the correct dilatational behaviour of the rock in compression. The combined yield surface along with an auxiliary criterion $f_{\mathrm{DP}}^{\mathrm{N}}$ exploited in stress return mapping (for details see Ref. [8]) is illustrated in Fig. 1.

The following softening/hardening laws for the cohesion, tensile strength, and hydrostatic strength (pressure in compression) of the material are chosen:

$$
\begin{aligned}
c &= c_0+h_{\mathrm{DP}}\kappa_{\mathrm{DP}}+s_{\mathrm{DP}}\dot{\kappa}_{\mathrm{DP}}\\
f_{\mathrm{t}} &= f_{\mathrm{t0}}+h_{\mathrm{MR}}\kappa_{\mathrm{MR}}+s_{\mathrm{MR}}\dot{\kappa}_{\mathrm{MR}}\\
p_{\mathrm{P}}(\varepsilon_V^{\mathrm{p}}) &= \frac{1}{D}\ln\left(1+\frac{\varepsilon_V^{\mathrm{p}}}{W}\right)+p_{\mathrm{P0}}
\end{aligned}
\qquad (2)
$$

where $h_{\mathrm{DP}}, h_{\mathrm{MR}}$ are the plastic softening/hardening moduli (set zero in this study) in compression and in tension, respectively. The viscosity moduli are denoted as s_{DP}, s_{MR} in compression and in tension, respectively. Moreover, $\varepsilon_V^{\mathrm{p}}$ is the plastic volumetric strain, p_{P0} is the initial (intact) value of pressure p_{P}, and D and W are parameters with physical meanings of the maximum plastic volumetric strain (W) and rate (D) (i.e. the initial slope of the $p_{\mathrm{P}}(\varepsilon_V^{\mathrm{p}})$ curve in quasi-static setting) at which the rock compaction occurs with increasing pressure. The stress integration (return mapping) of this model is performed with respect to the active surface in a standard manner. As for the choice of active surface, see Ref. [8].

The rate sensitivity in the current model is introduced by adding the product of viscosity and the rate of the internal variable to the static value of cohesion and tension in Equation (2). This means that the strain rate hardening effect can be obtained either by keeping the viscosity moduli fixed while increasing the loading rate or increasing the viscosities while keeping the loading rate fixed.

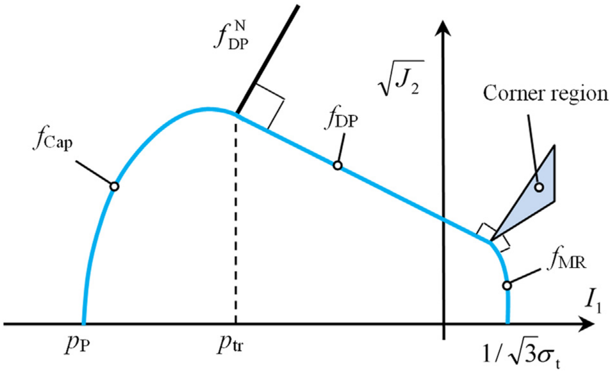

Fig. 1. DP-MR model with parabolic cap in I_1-$\sqrt{J_2}$ space.