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Research Paper

3D finite elements modelling of percussive rock drilling: Estimation of rate of penetration based on multiple impact simulations with a commercial drill bit

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ABSTRACT

This paper deals with assessing the rate of penetration (ROP) in percussive drilling of rock based on finite element simulations. For this end, a method to simulate the dynamic indentation in percussive drilling is developed and validated. This method includes a recently developed constitutive model to describe the rock fracture and a bit-rock interaction model. The constitutive model has a viscoplasticity part to indicate the stress states leading to rock fracture and a damage model with separate damage variables for tension and compression to quantify the rock fracture. In the numerical examples, the present approach is validated by simulations of the dynamic Brazilian disc test and dynamic indentation simulations on Kuru granite. The multiple consecutive impacts simulations carried out show that the present continuum approach is able to predict the experimental ROP. However, a close match of the experimental ROP requires that the critical damage threshold values, beyond which a damaged element contributes to the volume of removed material, are selected by the experiments. In any case, the present modelling approach, along with the procedure to convert the simulation results into ROP, provides a tool for improving the performance of percussive drilling equipment.

1. Introduction

Percussive drilling is still widely recognized as the most efficient excavation method in hard rock formations. In this method, the rock breakage is based on the dynamic indentation of the drill bit-buttons into the rock. More specifically, the impact induced stress waves force the bit to penetrate into the rock resulting in material removal through the crushing of the rock immediately beneath the buttons and by coalescence of the lateral cracks induced by the adjacent buttons. The performance of the drilling is usually expressed in terms of rate-of-penetration (ROP expressed in mm/min or m/h) of the bit. The ROP is a necessary parameter for the cost estimation and the planning of operations in rock engineering. Therefore, the numerical prediction of the ROP of a specific drill setup is an important task in the related engineering projects.

Experimental studies on the ROP and the bit-rock interaction laws in percussive drilling are plenty, see for example [1–5] and the references therein. However, the numerical studies addressing the prediction of the ROP seem rare in the literature. There are numerical studies, such as in [6,7] based on 1D modelling of the drill system dynamics where the bit-rock interaction law is usually an idealized bilinear curve based on experiments. Notwithstanding, genuine 3D modelling of the bit-rock interaction and the rock fracture is required to predict of the ROP of the drill setup; different fracture patterns (e.g. chipping phenomenon) may have similar penetration-force responses. Genuine 3D simulations of percussive drilling can also be used to optimize the bit design (the number of buttons, their geometry and location).

For these reasons, 3D numerical studies, with varying sophistication of details, on the bit-rock interaction in percussive drilling has been carried out by Saksala [8,9], Saksala et al. [10], Han et al. [11], Chiang and Elias [12], Saadati et al. [13], Zhu et al. [14], Bu et al. [15], and Fourmeau et al. [4]. However, only two of these works address the ROP prediction based on the simulations results. Namely, the paper by Han et al. [11] employed the FLAC3D code for percussive drilling simulation. However, the very coarse mesh, dictated by the large model size, and the element elimination strategy used in these simulations resulted in unrealistically high values of ROP (the six simulated impacts reached 0.35 m of damage depth). In the second paper by Saksala [9], the focus was on the influence of hydrostatic and confining pressure on the performance of the percussive drilling with a commercial bit. Single

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impact simulations were carried out using a damage-viscoplasticity model implemented in the finite element method. The ROP was estimated with a simple equation that relates the volume of damaged finite elements in the mesh to the experimental drilling frequency and the area of the drill hole. Due to the smeared sense of fracture description in this continuum modelling approach, the exact value of the ROP for a given drill setup and rock cannot be predicted. Instead, the threshold values of the damage variables (beyond which a finite element contributes to the volume of removed material) matching the experimental ROP must be identified from the experiments. In the conclusions in [9], a future research topic of validating the single impact simulation with multiple impact simulations with indexing the bit was suggested. This topic is dealt with here.

In the present paper, the rate of penetration in percussive drilling with a commercial 7-button bit on Kuru granite is estimated based on numerical simulations. For this end, a numerical modelling strategy based on the FEM developed in the above mentioned paper by Saksala [9] is adopted. However, the viscoplasticity part of the constitutive model for rock is modified so that the original model in compression based on the Drucker-Prager failure criterion with a parabolic compression cut-off is replaced by a model based on a power law criterion. This model was developed and validated in [16] for numerical modelling of the strain rate effects at highly confined compression of Kuru granite. The present study thus extends the validation of that model towards different applications. It should also be mentioned that the recently proposed power law criterion matches the confined compression experiments on Kuru granite better than the linear Drucker-Prager criterion used in [8–10].

The organization of the present paper is as follows. First, the theory of the numerical approach is presented briefly. Second, the model calibration with the material data and model parameters is explained. Third, the dynamic Brazilian disc and the dynamic indentation tests with a triple-button bit are simulated to demonstrate the performance of the model. Fourth, multiple impact simulations of percussive drilling with a 7-button bit are carried out and compared to the experiments. Finally, the paper is concluded with some discussion and final remarks.

2. Theory of numerical modelling

The theory of the numerical modelling, including the constitutive model for the rock and the dynamic bit-rock interaction model, is presented here. First, the constitutive model based on viscoplasticity and damage mechanics originally presented in [16] is explained briefly for the convenience of the reader. Then, the principle of the bit-rock interaction model is sketched. A more detailed account is given in [16].

2.1. Constitutive description of rock

The constitutive model for rock consists of a viscoplastic part and a damage part. The viscoplastic part indicate the stress states leading to rock failure and describes the inelastic deformation. The rock strain-rate sensitivity is accommodated in this part through viscosity. The damage part quantifies the failure by separate isotropic damage variables in compression and tension.

The stress states leading to the inelastic flow (failure) are indicated by a bi-surface yield criterion consisting of the power law criterion originally suggested in [17], called here the MH criterion (from the initials of the fourth author), for compressive (shear) fracture and the Modified Rankine (MR) criterion for the tensile fracture. Assuming perfectly viscoplastic behavior, these criteria are written as

$$
\begin{aligned}
&f_{\mathrm{MH}}(\boldsymbol{\sigma},\kappa_{\mathrm{MH}},\dot{\kappa}_{\mathrm{MH}}) = \sigma_1-\sigma_3 + B\sigma_1^n-\sigma_c(\dot{\kappa}_{\mathrm{MH}})\\
&f_{\mathrm{MR}}(\boldsymbol{\sigma},\kappa_{\mathrm{MR}},\dot{\kappa}_{\mathrm{MR}}) = \sqrt{\textstyle\sum_{i=1}^{3}\langle\sigma_i\rangle^2}-\sigma_t(\dot{\kappa}_{\mathrm{MR}}) \quad \text{with}\\
&\sigma_c(\dot{\kappa}_{\mathrm{MH}}) = \sigma_{c0} + s_{\mathrm{MH}}\dot{\kappa}_{\mathrm{MH}}, \quad \sigma_t(\dot{\kappa}_{\mathrm{MR}}) = \sigma_{t0} + s_{\mathrm{MR}}\dot{\kappa}_{\mathrm{MR}}
\end{aligned} \tag{1}
$$

where σ_i is the ith principal stress of the stress tensor $\boldsymbol{\sigma}$, σ_c, σ_t are the dynamic uniaxial compressive and tensile strengths of the material, and $\dot{\kappa}_{\mathrm{MH}}$, $\dot{\kappa}_{\mathrm{MR}}$ are the rates of the internal variables in compression and tension, respectively. Moreover, the McAuley brackets, i.e. the positive part operator, are used in the MH criterion while B and n in MH criterion are parameters to be calibrated experimentally. Finally, s_{MH}, s_{MR} are the constant viscosity moduli in compression and tension, respectively.

The rate sensitivity in this modelling approach is provided by adding the product of viscosity and the rate of the internal variable to the static values, σ_{c0}, σ_{t0}, of the compressive and tensile strength. This method is justified by the experimental results in [18] showing that the dynamic failure envelope of granite (Bukit Timah granite therein) can be obtained from the quasi-static one by translation, i.e. by adding a constant term to the compressive strength at each loading rate.

As for the damage part, separate scalar damage variables in tension and compression are used due to the highly asymmetric behavior of rocks in these stress regions. With the damage variables being driven by the viscoplastic strain, the damage functions (i.e., the integrated damage evolution equations) and the related field variables and parameters are specified as

$$
\begin{aligned}
&\omega_t(\varepsilon_{\mathrm{eqvt}}^{\mathrm{vp}}) = A_t(1-\exp(-\beta_t\varepsilon_{\mathrm{eqvt}}^{\mathrm{vp}})), \quad \omega_c(\varepsilon_{\mathrm{eqvc}}^{\mathrm{vp}}) = A_c(1-\exp(-\beta_c\varepsilon_{\mathrm{eqvc}}^{\mathrm{vp}})) \quad \text{with}\\
&\beta_t = \sigma_{t0}h_e/G_{\mathrm{Ic}}, \quad \beta_c = \sigma_{c0}h_e/G_{\mathrm{IIc}}\\
&\dot{\varepsilon}_{\mathrm{eqvt}}^{\mathrm{vp}} = \sqrt{\sum_{i=1}^{3}\langle\dot{\varepsilon}_i^{\mathrm{vp}}\rangle^2}, \quad \dot{\varepsilon}_{\mathrm{eqvc}}^{\mathrm{vp}} = \sqrt{\tfrac{2}{3}\dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}}:\dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}}} \quad \text{with}\\
&\dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}} = \dot{\lambda}_{\mathrm{MH}}\frac{\partial g_{\mathrm{MH}}}{\partial\boldsymbol{\sigma}} + \dot{\lambda}_{\mathrm{MR}}\frac{\partial f_{\mathrm{MR}}}{\partial\boldsymbol{\sigma}}, \quad \text{and}\\
&g(\boldsymbol{\sigma})_{\mathrm{MH}} = \sigma_1-\sigma_3 + m_pB\sigma_1^n, \quad m_p = \sin\psi
\end{aligned} \tag{2}
$$

where parameters A_t and A_c control the final value of the damage variables ω_t and ω_c in tension and in compression, respectively. The parameters β_t and β_c, which control the initial slope and the amount of damage dissipation, are defined by the fracture energies G_{Ic} and G_{IIc} and h_e is a characteristic length of a finite element. The equivalent viscoplastic strain in tension, $\varepsilon_{\mathrm{eqvt}}^{\mathrm{vp}}$, is defined by the ith principal value, $\dot{\varepsilon}_i^{\mathrm{vp}}$, of the viscoplastic strain rate tensor, $\dot{\boldsymbol{\varepsilon}}^{\mathrm{vp}}$, using the Macauley brackets so that tensile damage evolution occurs only if the viscoplastic principal strains are positive. The equivalent viscoplastic strain in compression, $\varepsilon_{\mathrm{eqvc}}^{\mathrm{vp}}$, is similar to that of the J_2-plasticity for metals. Moreover, Eq. (2)$_4$ is the Koiter's rule for bi-surface plasticity with $\dot{\lambda}_{\mathrm{MR}}$,$\dot{\lambda}_{\mathrm{MH}}$ being the viscoplastic multipliers in tension and in compression, respectively. As the associated flow rule tends to exaggerate the dilatation of rocks in compression, a plastic potential g_{MH} is used in Eq. (2)$_4$ with ψ being the dilation angle of the rock.

The combination of the damage and viscoplastic parts of the model is based on the effective stress space formulation (see [19]). This formulation enables the separation of viscoplastic and damage processes so that the return mapping is first performed independently of the damage process in the effective stress space. Then, the damage variables are updated and, finally, the nominal stress is computed with the following nominal-effective stress relation

$$
\boldsymbol{\sigma} = (1-\omega_t)\bar{\boldsymbol{\sigma}}_+ + (1-\omega_c)\bar{\boldsymbol{\sigma}}_- \quad (\bar{\boldsymbol{\sigma}} = \bar{\boldsymbol{\sigma}}_+ + \bar{\boldsymbol{\sigma}}_-) \tag{3}
$$

where $\bar{\boldsymbol{\sigma}}_+ = \max(\bar{\boldsymbol{\sigma}},0)$ and $\bar{\boldsymbol{\sigma}}_- = \min(\bar{\boldsymbol{\sigma}},0)$ are the positive and negative parts, respectively, of the principal effective stress. This formulation naturally conveys the strain rate dependency to the damaging as well. The stress integration (the return mapping of the trial stress onto the yield surface) for this viscoplastic consistency model is performed as in [20].

2.2. Percussive drilling simulation method

In percussive drilling, the key problem to be modelled is the dynamic bit-rock interaction. A simplified approach illustrated in Fig. 1 is adopted here. The drill rod is modelled using 2-node linear bar