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Numerical Modelling of Bit-Rock Interaction in Percussive Drilling

Timo Saksala[1]

[1] *Tampere University of Technology , Tampere, Finland, timo.saksala@tut.fi*

This paper considers numerical simulation of rock fracture in percussive drilling. An explicit dynamics FE procedure is presented for the simulation of dynamic bit-rock interaction. The methodology developed includes a constitutive model for simulating rock fracture in the continuum sense and a method for bit-rock interaction simulation. The constitutive model, presented originally by the author in [1], is based on a combination of the recent viscoplastic consistency model by Wang, the isotropic damage model, and a compression cap model. Viscoplasticity provides, under dynamic loading, a localisation limiter thus regulating the underlying initial/boundary value problem. It naturally introduces the strain rate effects as well.

Viscoplastic stress states are indicated by the Drucker-Prager (DP) yield function with the modified Rankine (MR) criterion as a tension cut-off. The ductile behaviour is governed by a parabolic cap surface smoothly fitted to the DP surface. The softening in tension is due to damaging while in compression the strength degradation is governed by a linear strain softening law calibrated with the degradation index, a material property proposed by Fang & Harrison [2]. Thereby, the model is able to capture the brittle-to-ductile transition phenomenon as the softening law depends on the confining pressure. Being combined with the parabolic compression cap the model is able to simulate the ductile (hardening) behaviour of rock beyond the brittle-to-ductile transition pressure. The response of the model at the material point level (using a single 8-node brick element) in confined compression is shown in Figure 1a. Below the brittle-to-ductile transition level (68.5 MPa) the model response is linear elastic up to peak strength and linearly softening until the residual strength. Therefore, the nonlinear response of the laboratory size specimen cannot be captured at the material point level. The peak and residual strengths are, however, matched with a reasonable accuracy. In contrast, at level 165 MPa of confinement, when the non-linear cap hardening plasticity is active, the experimental curve for Carrara marble is very accurately matched.

The microstructural heterogeneity of rock has a major influence on its failure processes. Here, the statistical method based on the Weibull distribution presented by Tang [3] is selected for characterising the rock strength heterogeneity at the mesoscopic level. By this approach the nonlinear response (such as the pre-peak nonlinearity) observed in the experiments is produced at the laboratory experiment level if the statistical characterisation of the rock strength heterogeneity is used [1, 3].

The principle for modelling the bit-rock interaction, originally implemented by the author in [4], is illustrated in Figure 1b. The drill bit is considered as a rigid body by idealising its buttons as nodes. The interaction with the rock is modelled using contact mechanics. Thence, the button geometry can be defined by kinematic contact constraints specifying the distances b_i between the virtual button surface and the contact nodes on the rock surface (see Figure 1b). The compressive wave forcing the bit penetration into the rock is simulated as an external stress pulse applied to the button node. As there is no drill rod in this method, a dashpot based on viscous damping is attached to the button node to absorb the stress wave thus simulating a long rod. Viscous dashpots are attached on the boundaries of the rock domain as well in order to prevent the stress wave reflections at the boundaries.

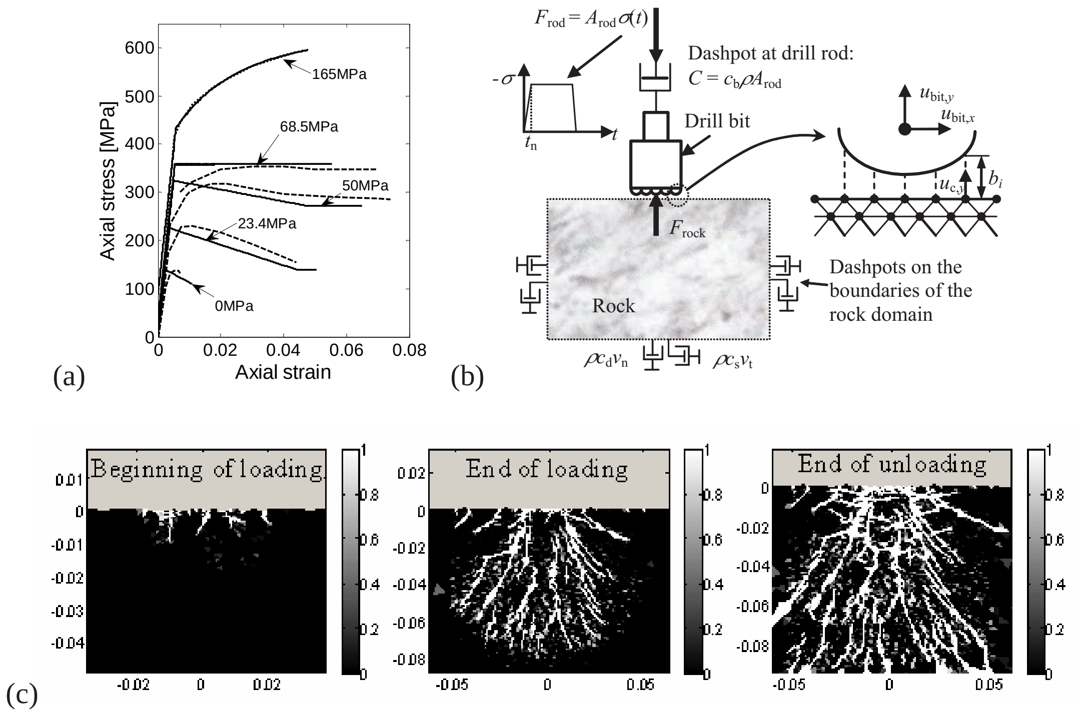

Figure 1.The response of the constitutive model at the material point level in confined compression for Carrara marble (dashed line) (a), principle of bit-rock interaction model (b), and damage distributions at different stages of loading in bit-rock interaction simulation with the present approach (c).

In case of the single button bit, this method adds only two (in 2D) degrees of freedom, $u_{\text{bit},x}$, $u_{\text{bit},y}$, to the overall computational model. In y-direction the equation of motion of a button reads: $m_{\text{bit}}\ddot{u}_{\text{bit},y} + c_{\text{b}}\rho A_{\text{rod}}\dot{u}_{\text{bit},y} = -A_{\text{rod}}\sigma(t) - F_{\text{rock}}$ where A_{rod} is a computational area of the rod cross section, F_{rock} is the (contact) force due to bit penetration, c_{b} is the bar velocity, ρ is the material density, m_{bit} is a computational (not real) bit mass, respectively. The contact constraints are imposed with the forward increment Lagrange multiplier method which is compatible with explicit time integrators. The bit-rock interaction is simulated under plane strain assumption.

An example of the simulation results is presented in Figure 1c where tensile damage distribution is plotted in the beginning and the end of loading phase, and in the end of unloading. Right-angled button has been used and the surface roughness of real rocks has been taken into account. The damage distributions display the Hertzian cone crack and mainly vertical crack formation in the end of loading phase. Concentric and side cracks resulting in chipping have been developed in the end of unloading. The main reason for these are the tensile stresses caused by the rapid unloading, i.e. the descent of the stress pulse. Finally, the elements just under the button are damaged which corresponds to the crushing of asperities in real in-situ drilling. This contributes positively to the reality of the results.

References

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