Predicting the Rate of Penetration in Percussive Drilling by Finite Elements Simulation*

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Abstract

Percussive drilling is a widely used drilling method, especially in hard rock formations, due to its efficiency in terms of rate of penetration (ROP). On the other hand, despite the considerable research effort devoted thus far, the fracture mechanisms in bit-rock interaction are not fully understood. In this method, an impact induced compressive stress wave forces hard metal inserts (bit buttons) in the drill bit to penetrate into the rock. The penetration results in material removal through direct fragmentation of the rock beneath the buttons and, more importantly, by the coalescence of the side cracks (lateral chips) induced by individual buttons. The debris and fragments are flushed away from the borehole during the action. The drill bit is also rotated between the impacts in order to improve the process (impacting the same spots many times would halt the penetration eventually). In the development and optimization of drill bits, sound understanding of these fracture mechanisms is crucial.

In the present work, a finite element based numerical code is employed in an attempt to predict the rate of penetration during percussive drilling with a typical multiple-button bit. In this method, the rock is described as a viscoplastic damaging material and the bit-rock interaction is modelled by contact mechanics approach while solving the system equations with explicit time marching. The stress states leading to material damage are indicated by a rate-dependent three-surface yield surface consisting of the Drucker-Prager criterion, Rankine criterion as a tensile cut-off, and a parabolic cap surface as a compression cut-off. Thus, porous rocks can also be modelled. Due to the high asymmetry of the rock behavior in tension and compression, separate scalar damage variables are defined to account for failure in tension and compression. Thereby, the material removal is indicated by critical values of these damage variables. A criterion to predict the ROP based on single impact is first developed. Then, multiple impacts while rotating the bit between the impacts (indexing) are simulated in order to demonstrate the validity of the single impact ROP prediction scheme.

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Predicting the rate of penetration in percussive drilling by finite elements simulation

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Resonator AS, a Norwegian company developing efficient high frequency electric rock drills for oil drilling, is the initiator and funder of this research

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GEO 2018
13th Middle East Geosciences Conference and Exhibition

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2. Constitutive model for rock
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5. The effect of confinement in drilling deep holes
6. Predicting the ROP in percussive drilling by single and multiple blow simulations

1. Background and motivation

- Percussive drilling is the method for hard rock drilling
- In order to develop more efficient drill tools, a numerical method with predictive capabilities is highly desired since it reduces the R&D cost (by reducing the need for prototype manufacturing and lab testing)
- Finite element method is a mature numerical method that is computationally superior, in terms of efficiency, to discrete/particle element methods
- A method to predict ROP with the FEM should therefore be developed

2. Constitutive model for rock

- ***Rock is described as a continuous viscoplastic damaging material***
  - Stress states leading to failure of rock are indicated by a tri-surface criterion consisting of the Drucker-Prager yield function with a Rankine criterion as a tension cut-off and a parabolic cap-surface as a compression cut-off.
  - Viscoplasticity accounts for the loading-rate sensivity of rock, that is the strain-rate hardening effects, which are important in the dynamic bit-rock interaction process during percussive drilling.
  - Isotropic damage model with separate damage variables for tension and compression governs the tensile and compressive (shear) type of failures of rock.
  - Compression cap accounts for the compactive deformation behavior of rock under the buttons.

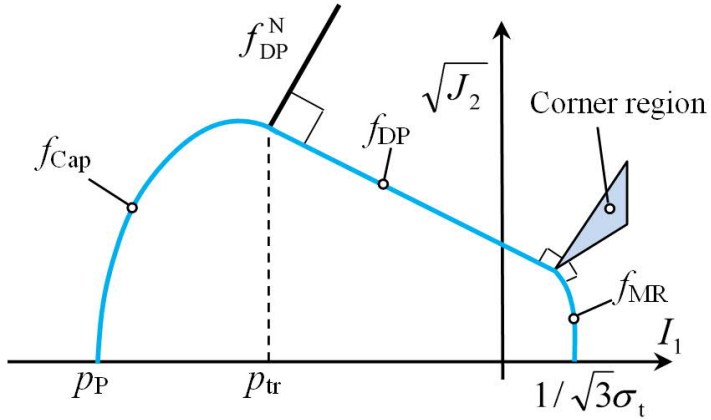
2. Constitutive model for rock

Yield/failure multi-surface

$$f_{\mathrm{DP}}(\boldsymbol{\sigma}, \kappa_{\mathrm{DP}}, \dot{\kappa}_{\mathrm{DP}}) = \sqrt{J_2} + \alpha_{\mathrm{DP}} I_1 - k_{\mathrm{DP}} c(\kappa_{\mathrm{DP}}, \dot{\kappa}_{\mathrm{DP}})$$

$$f_{\mathrm{MR}}(\boldsymbol{\sigma}, \kappa_{\mathrm{MR}}, \dot{\kappa}_{\mathrm{MR}}) = \sqrt{\textstyle\sum_{i=1}^{3} \langle \sigma_i \rangle^2} - f_{\mathrm{t}}(\kappa_{\mathrm{MR}}, \dot{\kappa}_{\mathrm{MR}})$$

$$f_{\mathrm{Cap}}(\boldsymbol{\sigma}, c, p_{\mathrm{p}}) = \sqrt{J_2} - C_1(c, p_{\mathrm{p}}) I_1^2 - C_2(c, p_{\mathrm{p}}) I_1 - C_3(c, p_{\mathrm{p}})$$



Viscoplastic flow potential and parameter definitions

$$g_{\mathrm{DP}} = \sqrt{J_2} + \beta_{\mathrm{DP}} I_1 - C \qquad \alpha_{\mathrm{DP}} = 2\sin\varphi/(3-\sin\varphi) \quad k_{\mathrm{DP}} = 6\cos\varphi/(3-\sin\varphi) \quad \beta_{\mathrm{DP}} = 2\sin\psi/(3-\sin\psi)$$

Smooth transition between the cap to DP cone flow by conditions

$$\begin{cases} -\alpha_{\mathrm{DP}} p_{\mathrm{tr}} + \kappa_{\mathrm{DP}} = C_1 p_{\mathrm{tr}}^2 + C_2 p_{\mathrm{tr}} + C_3 \\ -\beta_{\mathrm{DP}} = 2C_1 p_{\mathrm{tr}} + C_2 \\ 0 = C_1 p_{\mathrm{P}}^2 + C_2 p_{\mathrm{P}} + C_3 \end{cases}$$

$$p_{\mathrm{tr}} = \frac{p_{\mathrm{P}}(\varepsilon_V^{\mathrm{p}})}{p_{\mathrm{P0}}} p_{\mathrm{tr0}} = p_{\mathrm{P}}(\varepsilon_V^{\mathrm{p}}) k_{\mathrm{p}}$$

Auxiliary surface for active surface detection scheme

$$f_{\mathrm{DP}}^{\mathrm{N}} = \sqrt{J_2} - \alpha_{\mathrm{DP}}^{-1} I_1 - \kappa_{\mathrm{DP}}^{\mathrm{N}}, \; \kappa_{\mathrm{DP}}^{\mathrm{N}} = p_{\mathrm{tr}}(\alpha_{\mathrm{DP}} + \alpha_{\mathrm{DP}}^{-1}) + \kappa_{\mathrm{DP}} c(\lambda_{\mathrm{DP}}, \dot{\lambda}_{\mathrm{DP}})$$

2. Constitutive model for rock

Active surface detection scheme

1. $f_{\mathrm{DP}}^{\mathrm{N}} > 0$

   If $f_{\mathrm{Cap}}^{\mathrm{trial}} > 0 \rightarrow$ cap plasticity

   Else $\rightarrow$ elastic process

2. $f_{\mathrm{DP}}^{\mathrm{N}} \leq 0$

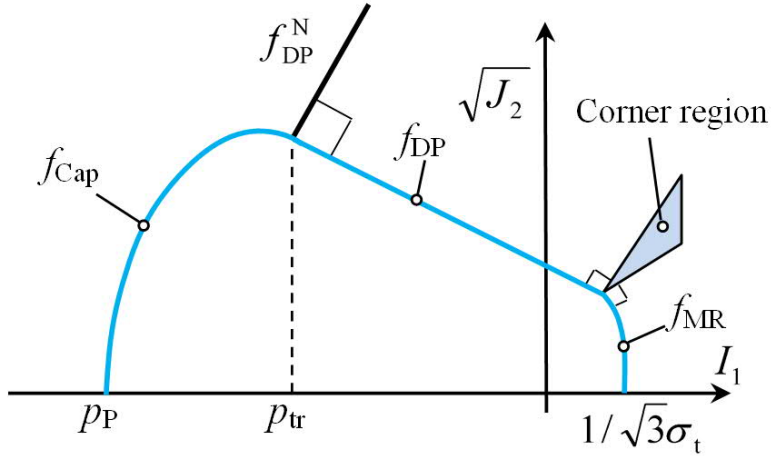
   If $I_1^{\mathrm{trial}} < p_{\mathrm{tr}}$ & $f_{\mathrm{Cap}}^{\mathrm{trial}} > 0 \rightarrow$ cap plasticity

   Elseif $f_{\mathrm{DP}}^{\mathrm{trial}} > 0$ & $f_{\mathrm{MR}}^{\mathrm{trial}} > 0 \rightarrow$ MR - DP viscoplasticity

   Elseif $f_{\mathrm{DP}}^{\mathrm{trial}} > 0$ & $f_{\mathrm{MR}}^{\mathrm{trial}} \leq 0 \rightarrow$ DP viscoplasticity

   Elseif $f_{\mathrm{DP}}^{\mathrm{trial}} \leq 0$ & $f_{\mathrm{MR}}^{\mathrm{trial}} > 0 \rightarrow$ MR viscoplasticity

   Else $\rightarrow$ elastic process



Rate dependent tensile strength and cohesion, rate-independent cap hardening law

$$c = c_0 + \underbrace{h_{\mathrm{DP}}}_{=0} \kappa_{\mathrm{DP}} + s_{\mathrm{DP}} \dot{\kappa}_{\mathrm{DP}}, \quad f_{\mathrm{t}} = f_{\mathrm{t0}} + \underbrace{h_{\mathrm{MR}}}_{=0} \kappa_{\mathrm{MR}} + s_{\mathrm{MR}} \dot{\kappa}_{\mathrm{MR}}$$

$$p_{\mathrm{P}}(\varepsilon_V^{\mathrm{p}}) = \tfrac{1}{D} \ln(1 + \tfrac{\varepsilon_V^{\mathrm{p}}}{W}) + p_{\mathrm{P0}}$$

Ideally viscoplastic behavior!

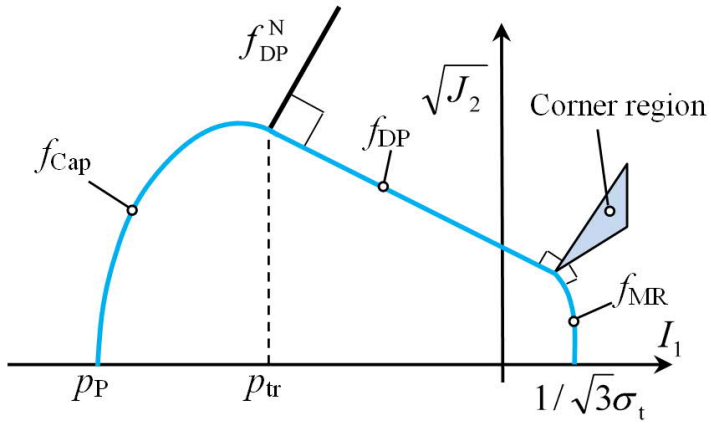
2. Constitutive model for rock

Damage formulation

$$\omega_t(\varepsilon_{eqvt}^{vp}) = A_t\left(1-\exp\left(-\beta_t \varepsilon_{eqvt}^{vp}\right)\right), \quad \omega_c(\varepsilon_{eqvc}^{vp}) = A_c\left(1-\exp\left(-\beta_c \varepsilon_{eqvc}^{vp}\right)\right)$$

$$\dot{\varepsilon}_{eqvt}^{vp} = \sqrt{\textstyle\sum_{i=1}^{3}\langle \dot{\varepsilon}_i^{vp}\rangle^2}, \quad \dot{\varepsilon}_{eqvc}^{vp} = \sqrt{\tfrac{2}{3}\dot{\boldsymbol{\varepsilon}}^{vp} : \dot{\boldsymbol{\varepsilon}}^{vp}} \quad \text{with}$$

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\lambda}_{DP}\frac{\partial g_{DP}}{\partial \boldsymbol{\sigma}} + \dot{\lambda}_{MR}\frac{\partial f_{MR}}{\partial \boldsymbol{\sigma}}$$



Given $\boldsymbol{\varepsilon}_{t+\Delta t} = \mathbf{B}\mathbf{u}^{e}_{t+\Delta t}$ Do:

1. Predict trial elastic stress state:

   $\bar{\boldsymbol{\sigma}}_{trial} = \mathbf{E} : (\boldsymbol{\varepsilon}_{t+\Delta t} - \boldsymbol{\varepsilon}_t^{vp}) \rightarrow \bar{\boldsymbol{\sigma}}_{trial}^{pr}$ (principal stresses)

   $f_{DP}^{trial} = f_{DP}(\bar{\boldsymbol{\sigma}}_{trial}^{pr}, \kappa_{DP}^t, \dot{\kappa}_{DP}^t), \; f_{MR}^{trial} = f_{MR}(\bar{\boldsymbol{\sigma}}_{trial}^{pr}, \kappa_{MR}^t, \dot{\kappa}_{MR}^t)$

   $f_{Cap}^{trial} = f_{Cap}(\bar{\boldsymbol{\sigma}}_{trial}^{pr}, c^t, p_P^t)$

2. If $\max(f_{MR}^{trial}, f_{DP}^{trial}, f_{Cap}^{trial}) > 0$

   Perform *Viscoplastic correction* $\rightarrow \bar{\boldsymbol{\sigma}}^{t+\Delta t}, \boldsymbol{\varepsilon}_{t+\Delta t}^{vp}$

   Otherwise elastic state correct $\rightarrow$ EXIT

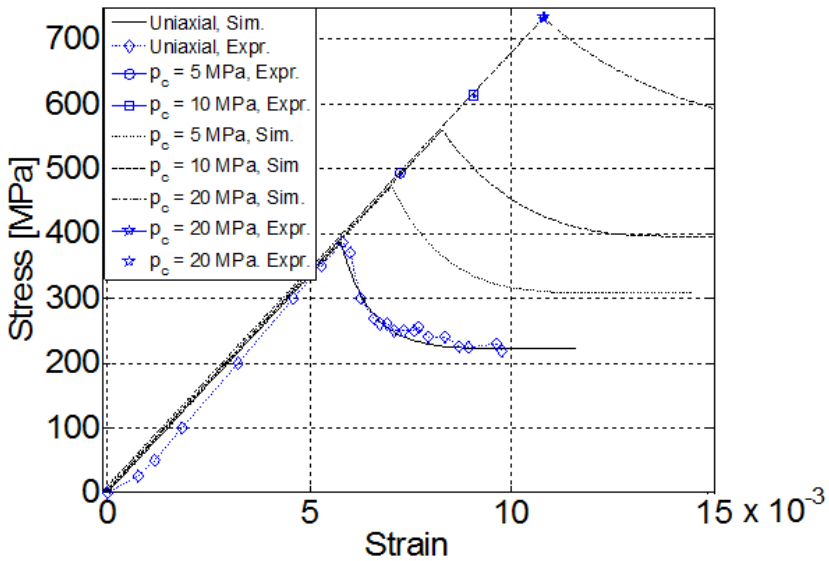
3. Update damage variables:

   $\omega_t^{t+\Delta t} = g_t(\varepsilon_{eqvt}^{vp,t+\Delta t}), \quad \omega_c^{t+\Delta t} = g_c(\varepsilon_{eqvc}^{vp,t+\Delta t})$

4. Calculate nominal stress:

   $\boldsymbol{\sigma}^{t+\Delta t} = (1-\omega_t^{t+\Delta t})\bar{\boldsymbol{\sigma}}_+ + (1-\omega_c^{t+\Delta t})\bar{\boldsymbol{\sigma}}_- \quad (\bar{\boldsymbol{\sigma}}^{t+\Delta t} = \bar{\boldsymbol{\sigma}}_+ + \bar{\boldsymbol{\sigma}}_-)$

Calibration in uniaxial compression

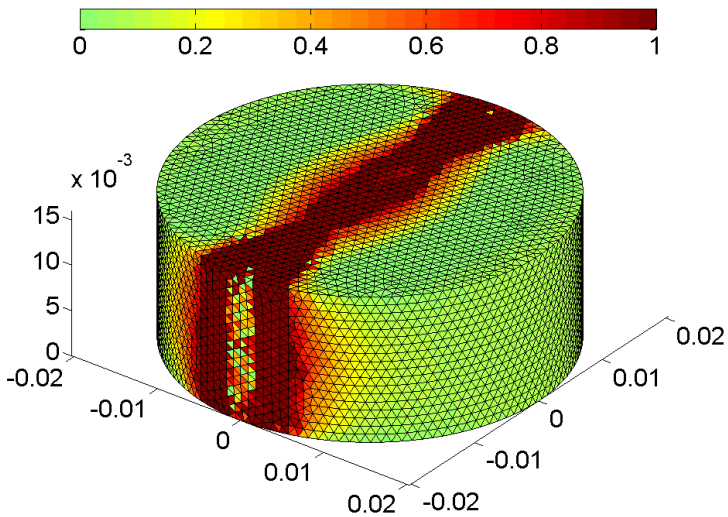


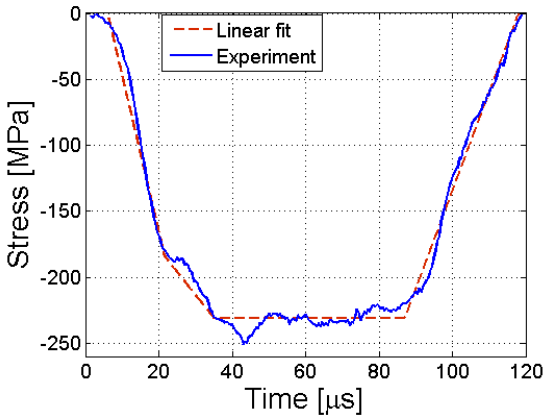
2. Constitutive model for rock

Dynamic Brazilian test on Kuru granite for adjusting the viscosity moduli: s_{RM} = 0.16 MPas and s_{DP} = 0.1 MPas

Experiment

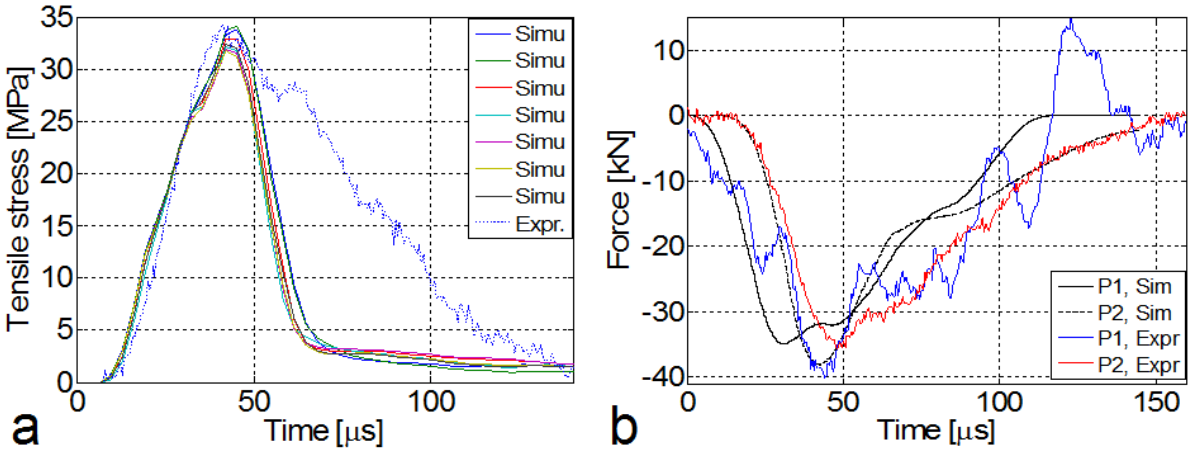
Simulation





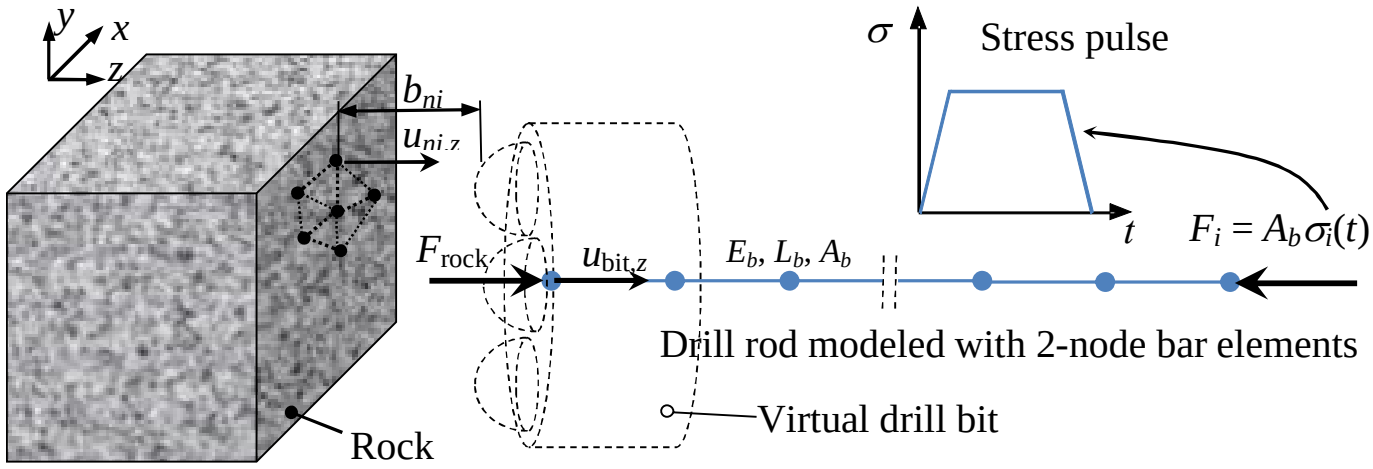
Input stress pulse

Simulated and experimental tensile stresses (a) and reaction forces (b)



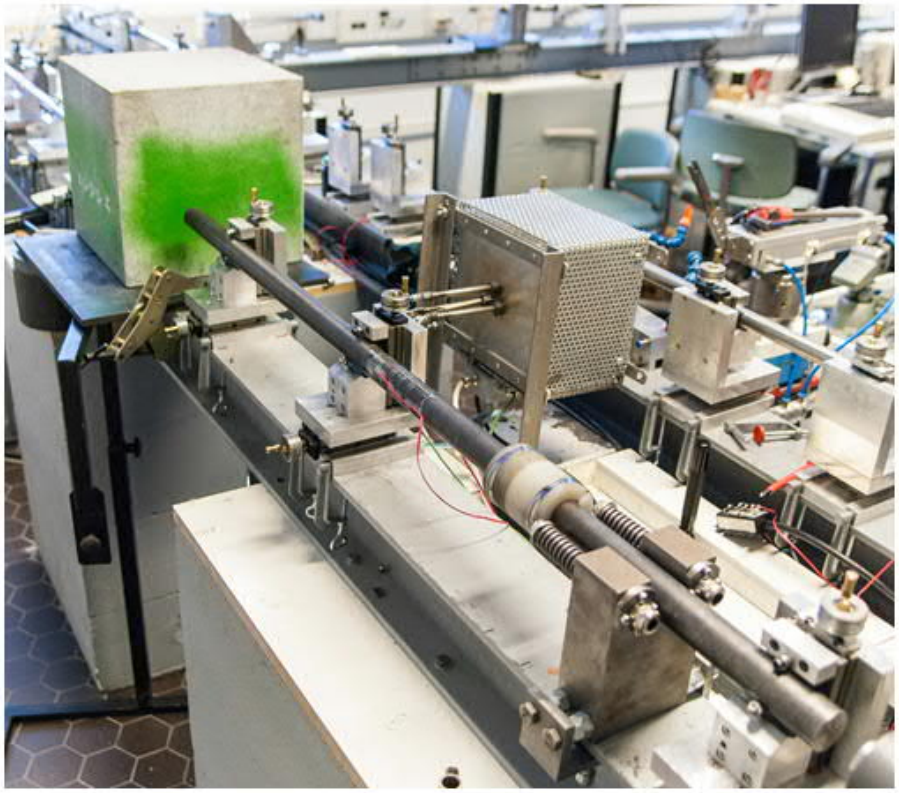
3. Percussive drilling simulation model

- The bit-rock interaction is modelled using the finite element method and contact mechanics by imposing the impenetrability conditions between buttons and rock: *the drill bit is taken as a rigid body but the drill rod is elastic 1D structure*
- Drill rod is modelled with 2-node bar elements while the impact of the piston is taken into account as a boudary condition
- ***Various number of buttons and different button geometries can be easily modelled***

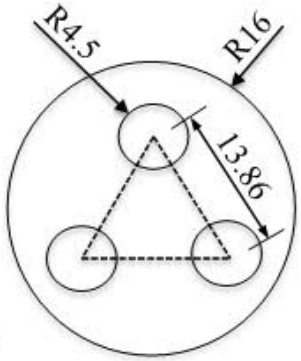


4. Validation of the model for Kuru granite

Dynamic indentation tests with a special triple-button bit

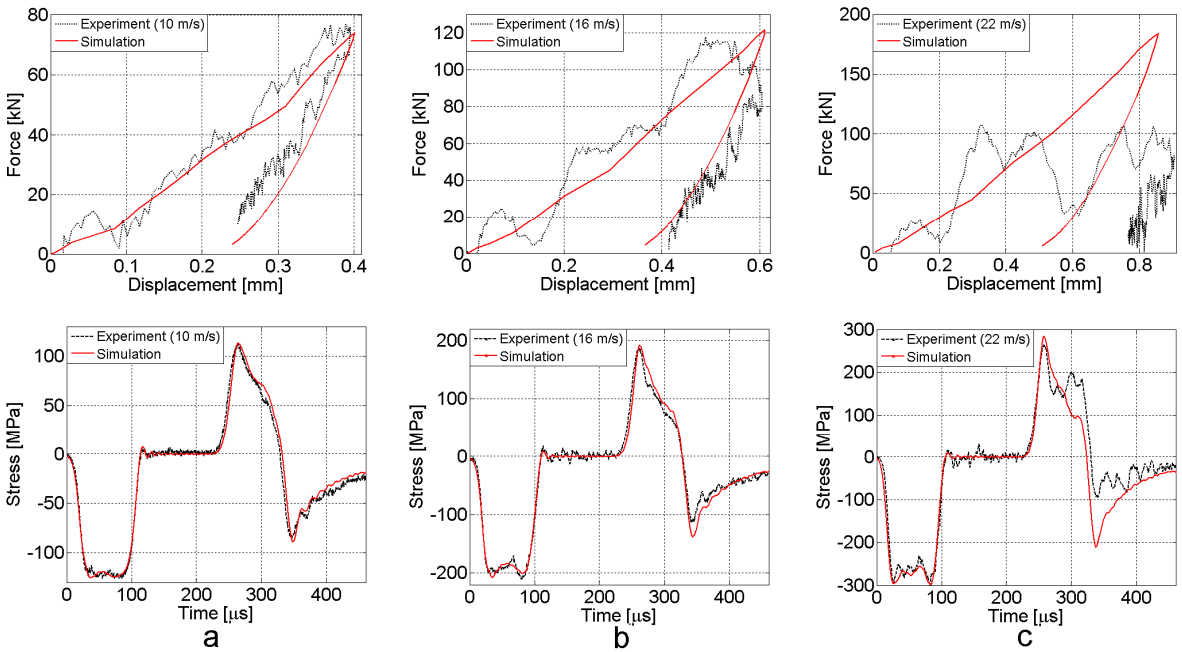


a

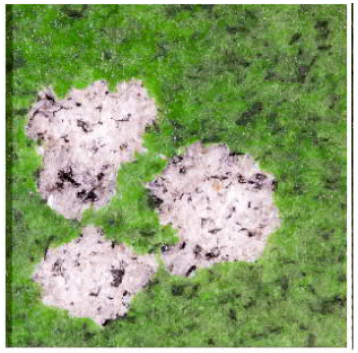


b

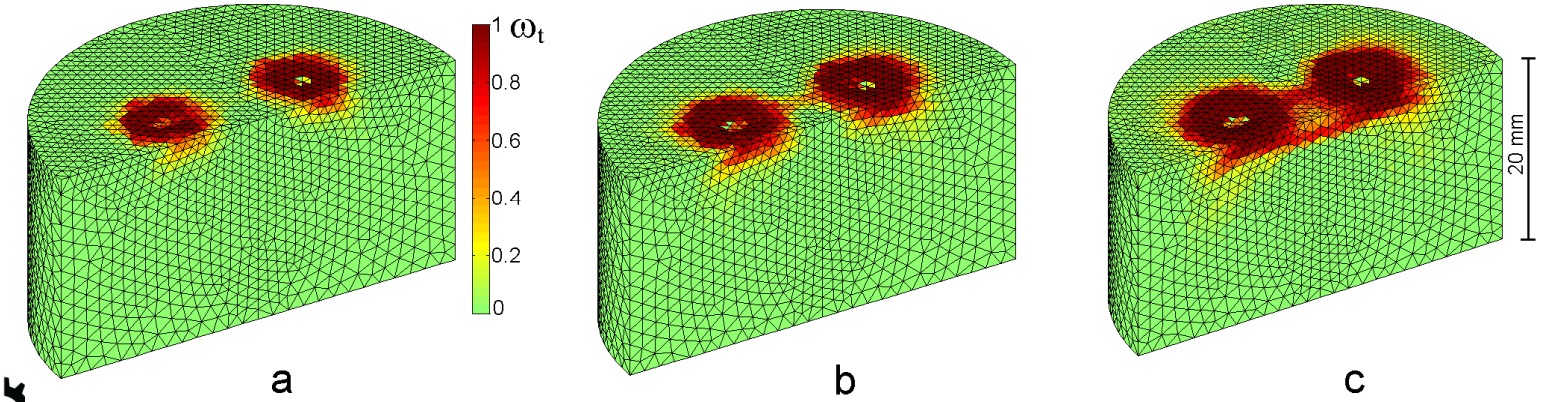
4. Validation of the model for Kuru granite



16 m/s

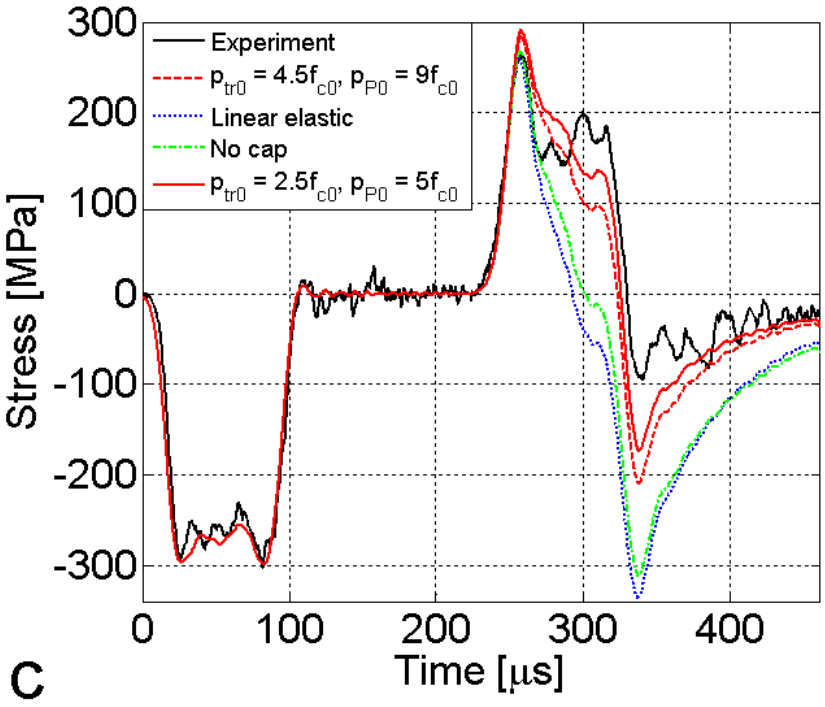


22 m/s

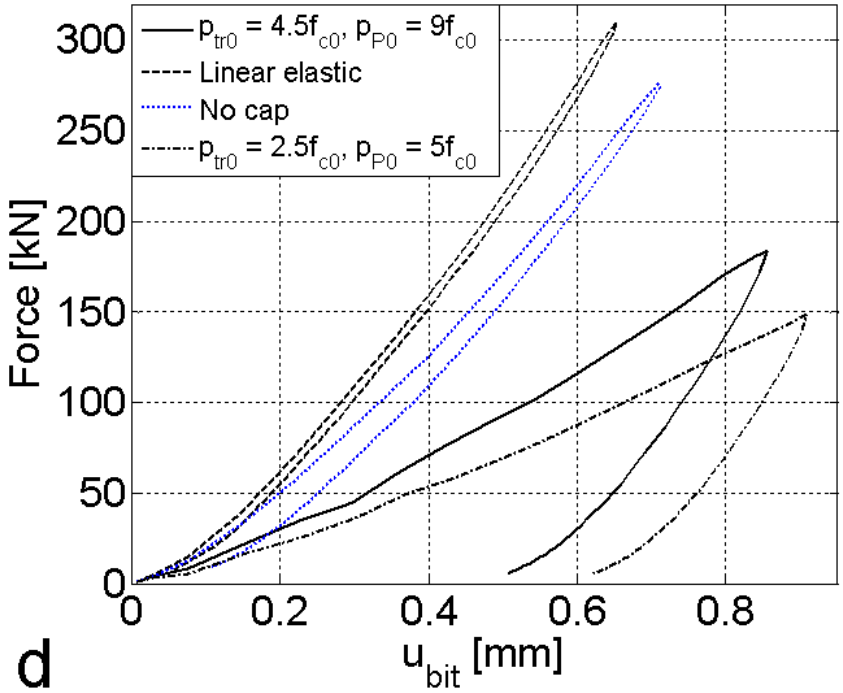


4. Validation of the model for Kuru granite

Influence of cap model



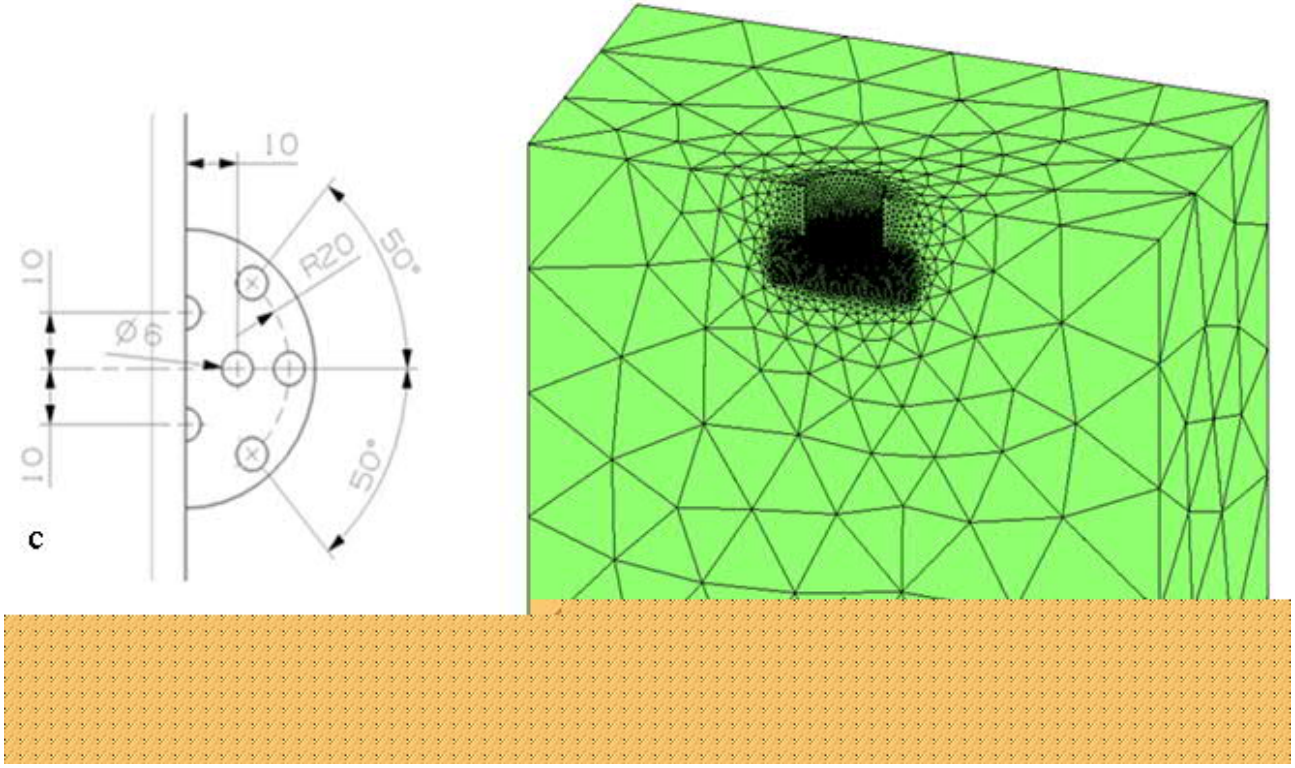
c



d

5. Effect of confinement at high depths

- Effect of hydrostatic pressure on percussive drilling with a fictional 10-button bit was simulated.
- The bit design and the finite element mesh are shown below.
- Half symmetry is exploited.

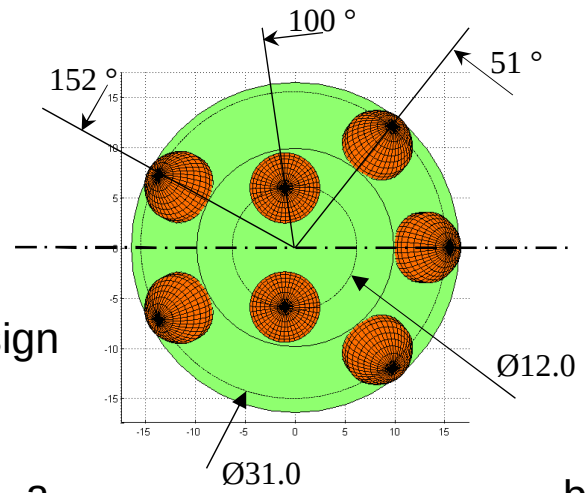


6. Predicting the ROP in percussive drilling by single and multiple blow simulations

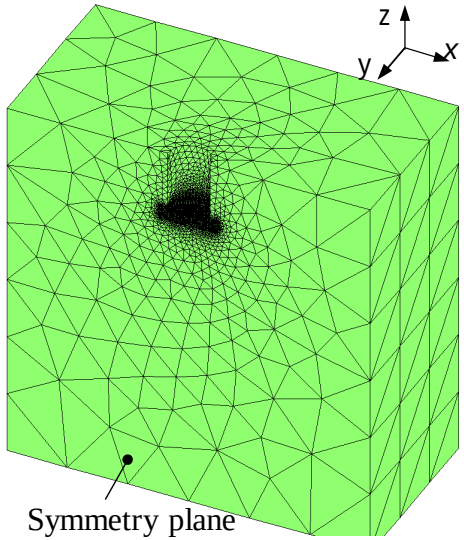
Drilling technical assumptions:

1. Drill rod is 2 m long and its cross-sectional area is 384 mm^2 (half of is used in the simulations due to the half-symmetry exploitation).
2. The semi-ballistic buttons are approximated as hemispherical ones with radius 2.5 mm.
3. All buttons are positioned at the same level in the drilling direction so that their contact on the flat borehole bottom occurs simultaneously.
4. The diameter of the borehole is 35 mm in the simulations which, when the gauge button contact area centers are located on the sphere ∅31, gives 2 mm length in radial direction to accommodate the contacts of the edge buttons (their radius is 2.5 mm).

Bit design



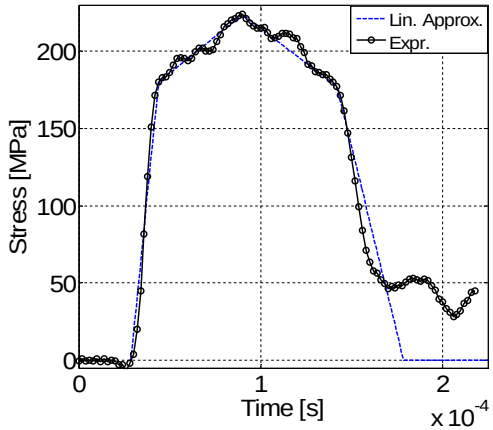
a



b

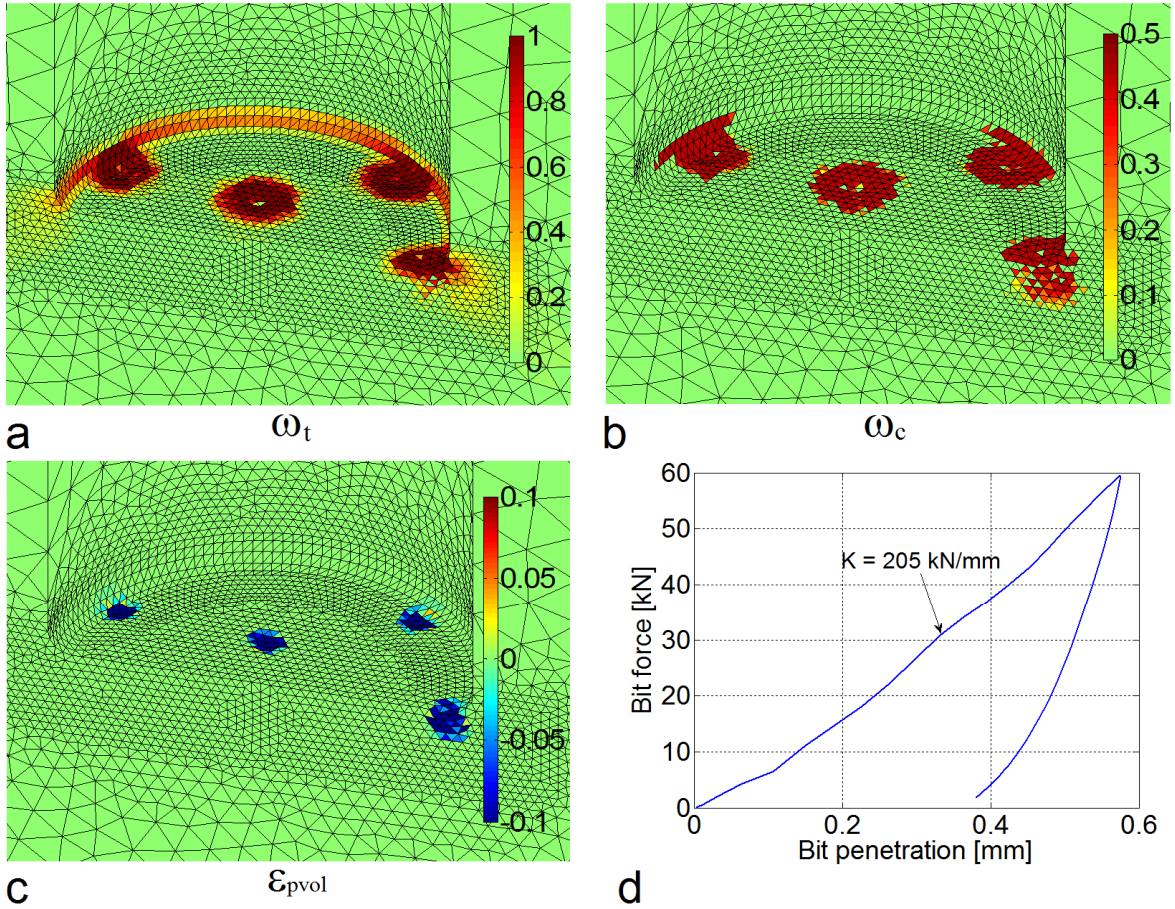
Tetrahedral mesh 168k els

Input compressive pulse



6. Predicting the ROP in percussive drilling by single and multiple blow simulations

Example of simulation results in single-blow case



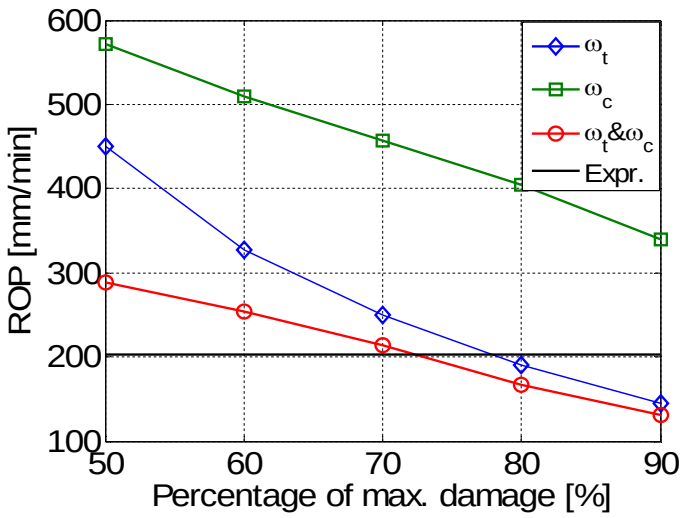
6. Predicting the ROP in percussive drilling by single and multiple blow simulations

Estimation of ROP based on single-implact simulation

$$ROP_{\text{sim}} = \frac{60\,f}{N_{\text{imp}}} \frac{V_{\text{sim}}}{A_{\text{hole}}}$$

where f is the impact frequency, N_{imp} is the number of impacts, V_{sim} is the volume of the failed elements, and A_{hole} is the drill hole area.

- Experimental value ROP = 203 mm/min with f =19.6 Hz in the unconfined case was provided by Resonator.

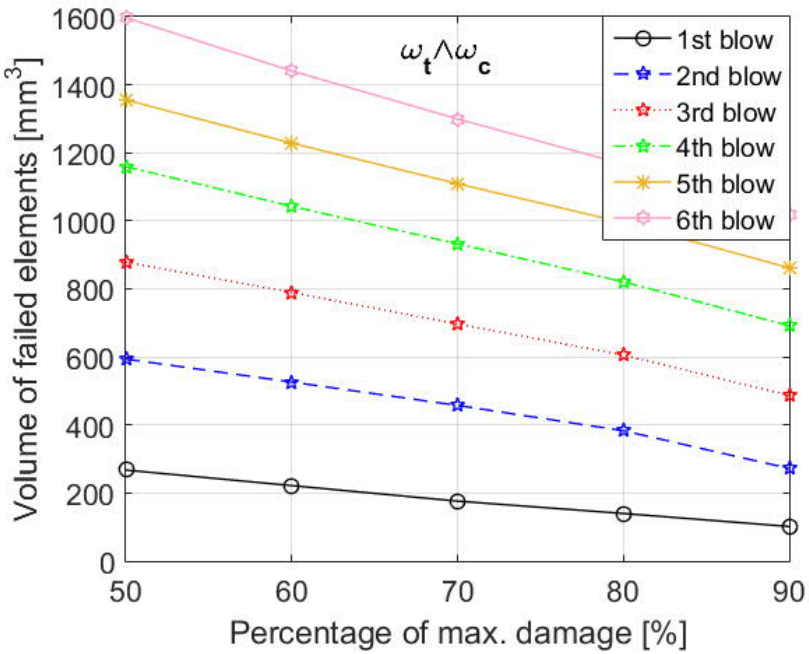


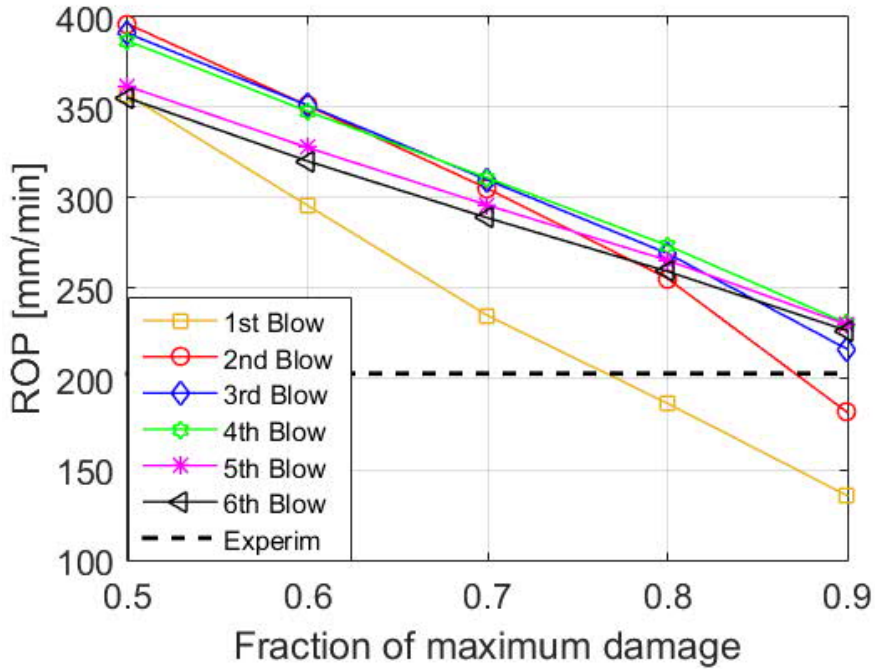
The threshold percentages in different damage modes matching the experimental ROP can be read as 72 % for ω_c&ω_t and 78 % for ω_t

The ω_c&ω_t mode with the threshold fraction 0.72 is chosen for plotting the pressure vs. ROP curve.

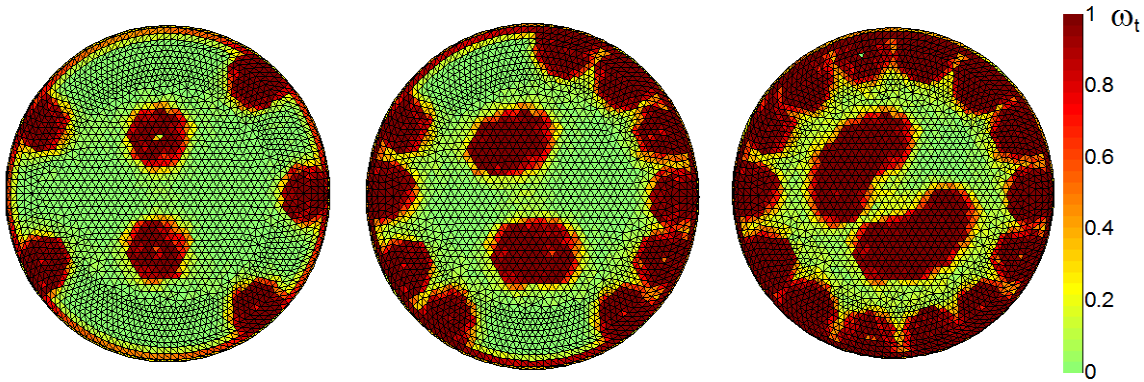
6. Predicting the ROP in percussive drilling by single and multiple blow simulations

- In order to check the validity of single-blow predicted ROPs, multiple impacts should be simulated
- Six impacts were simulated while rotating the bit 26 degrees between each impact



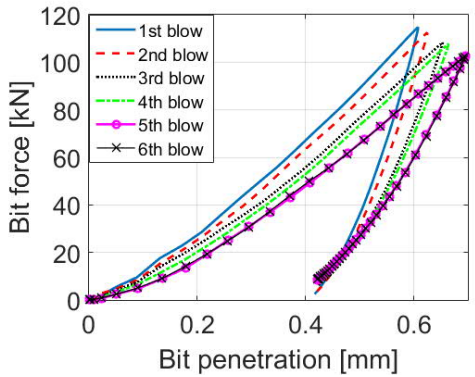


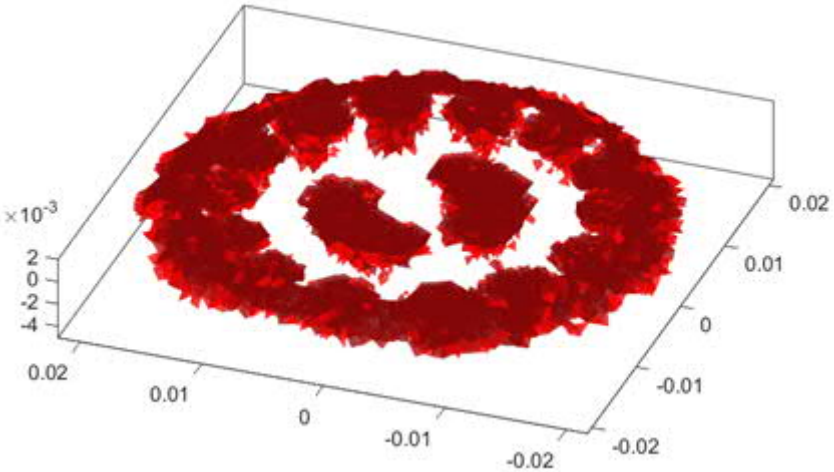
6. Predicting the ROP in percussive drilling by single and multiple blow simulations



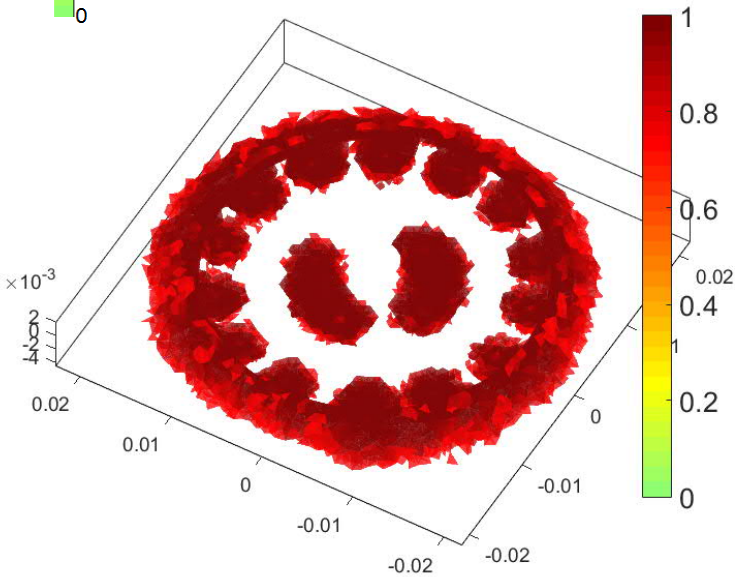
Tensile damage after 1st, 2nd and 4th impact

Bit force-penetration curves





Compressive damage



Tensile damage

Conclusions

- A numerical method, based on finite elements and a damage-viscoplastic constitutive model for rock, for percussive drilling simulation was developed, with a special emphasis on ROP prediction of a given drill set-up
- The major drawback of the method is the smeared crack description which complicates, due to the continuous nature of crack, the ROP prediction
- In any case, keeping in mind the limitations of the continuum approach to describe the rock fracture, the present approach could be a useful tool in the research and development of the pertinent fields of rock engineering