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Three-Dimensional Numerical Study of DTH Bit–Rock Interaction with HPWJ Downhole Slotting: Influence of Bit Design and Bottom Hole Geometric Conditions on Rock Breaking Efficiency in Percussive Drilling

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ABSTRACT

In the context of the EU project H2020 ORCHYD aiming at increasing hard rock drilling rate in deep geothermal wells, 3D finite element simulations of bit-rock interactions were performed to assess how by combining High Pressure Water Jetting (HPWJ)-made groove and bottom-hole geometry can contribute to improve the down-hole percussive performance. Twelve different groove depth-bottom-hole configurations were investigated. A Red Bohus granite rock was modelled using a continuum, plasticity-based, damage model calibrated using uniaxial and triaxial experimental test data. The presence of the groove affects both impact load and penetration. The groove also affects the amount and extent of damage around and between indents, especially near the groove, as well as the total volume fractured, or removed. It is finally found that the presence of a groove is significantly beneficial only for some specific bit profiles.

1. INTRODUCTION

This study is performed in the context of the EU project ORCHYD (2021), where an innovative drilling tool, combining high pressure water jetting and percussive drilling, will be developed to increase hard rock drilling rates in deep geothermal wells.

The role, at the bit-rock interaction, of the loading and profile conditions on the hard rock percussive breaking efficiency has been investigated in various experimental and numerical studies. These studies have highlighted in particular the decrease of rock breaking efficiency and rate of penetration (ROP) with an increase of confining pressure, the nonlinear (with a tendency to saturation) effect of an increasing impact energy on the rock breaking efficiency and the potential increase of the mechanical specific energy from a flat surface (limiting the number of buttons impacting the rock) to a parabolic surface – see Fourmeau et al. (2015), Fourmeau et al. (2017), Saksala et al. (2013), Saksala et al. (2014), Saksala et al. (2016), Saadati et al. (2014). However, the potential use of high pressure water jetting (HPWJ), at the bit-rock interaction, to generate a rock profile that can maximize the percussive drilling efficiency remains poorly explored.

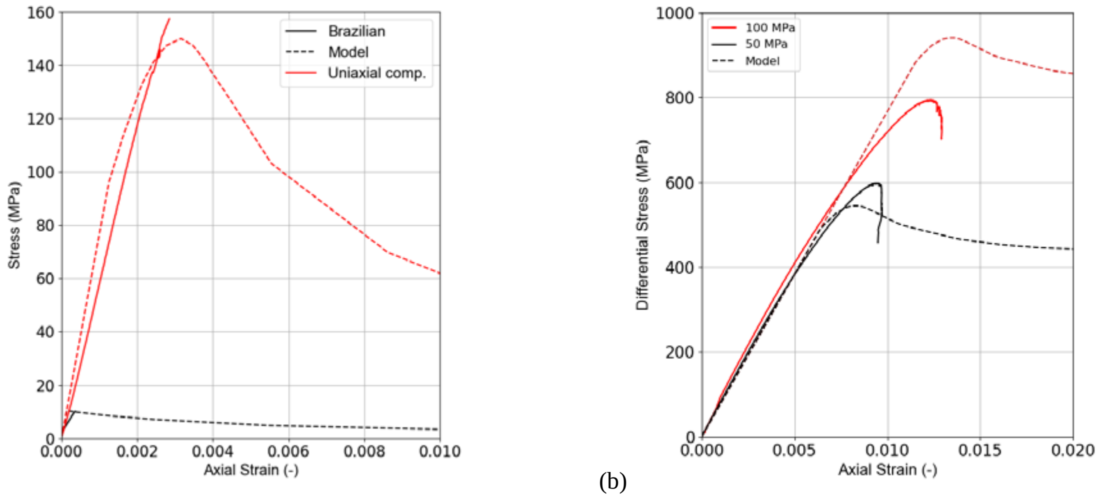
In this paper we have numerically investigated how grooves, created with a HPWJ system on the bottom-hole, can contribute to improve the down-hole percussive performance. Parametric finite element (FE) simulations (3D) were therefore carried out in order to assess the influence of various bit designs and bottom hole profiles on the rock breaking efficiency. Four different bit geometries were modelled (flat, parabolic, pure-parabolic and concave) with their associated bottom hole profiles (assuming idealized surfaces at steady state conditions) and by considering various peripheral groove depths (3 mm wide groove with 3 depths: 0, 10, 30 mm).

Single impact simulations were performed on Red Bohus granite rock under representative deep impact loading conditions, with representative weight-on-bit, bit mass, impact velocity and confining pressure. The pressure and rate dependency on the granite rock breaking process under impact – see Hokka et al. (2016), Tkalich et al. (2017), Saksala et al. (2017) – are captured with use of an elasto-plastic and damage model for hard rock (Concrete Damage Plasticity model in Abaqus), calibrated against uniaxial compression static tests and triaxial static tests done on the selected Red Bohus (compressive tests with confining pressure varying from 0 to 100 MPa).

The organization of the present paper is as follows. First, the experimental background used for the rock model calibration is presented. Second, the modelling approach, with the model parameters and the FE configurations, is explained. Third, the results are presented and discussed, and finally summarized in the conclusion.

2. EXPERIMENTAL BACKGROUND

The rock used in the current study is the Red Bohus granite which is extracted in the southwestern part of Sweden. It is composed of 60wt% feldspar, 35wt% quartz and 5wt% biotite. Feldspars have sizes that can be larger than several millimetres. Uniaxial compression and Brazilian tests were performed at room temperature and low strain-rates, see Figure 1(a). Triaxial compression tests under different confining pressures were performed at room temperature and at low strain-rate, see Figure 1(b). Dynamic indentation tests under different confining pressures, weight on bits and impact energies performed in another study were also used here; see Aldannawy et al. (2022) for more details.



(a) (b)

Figure 1: (a) stress versus strain from uniaxial compression and Brazilian test (left); (b) differential stress versus axial strain from triaxial tests with confining pressure of 50 and 100 MPa (right); the curves from the numerical model are shown with dashed lines.

3. MODELLING APPROACH

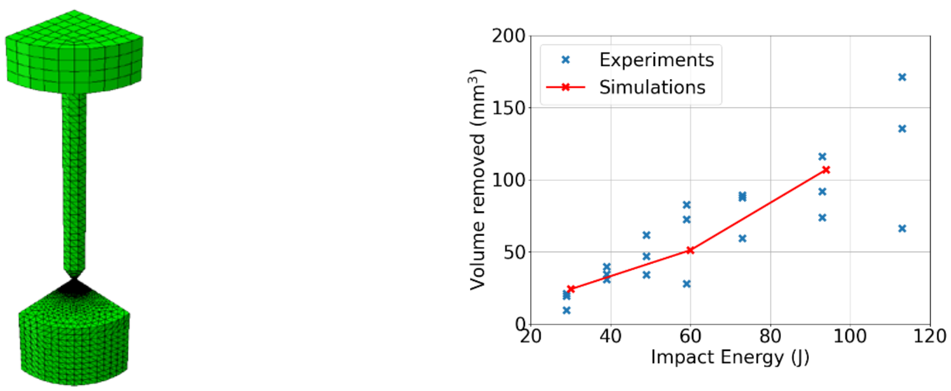
The model used in the current study is a continuum, plasticity-based, damage model, namely the concrete damage plasticity (CDP) model available in the commercial finite element software Abaqus (2022). It is a continuum model with a non-associated potential plastic flow and isotropic damage elasticity. The inelastic behaviour is described with tensile and compressive plasticity, including damage and strain-rate sensitivity. Strain-rate sensitivity (SRS) was accounted for in compression using dynamic increase factors from Liu et al. (2018); no strain rate sensitivity was used in tension as this proved being numerically unstable.

At first, the model was calibrated against uniaxial compression and triaxial tests using one axisymmetric element. The model parameters obtained are given in Table 1. The response of the model under triaxial conditions is shown in Figure 1. In all simulations, full recovery in compression and no recovery in tension was assumed.

Table 1: Model parameters.

Young modulus	w	Eccentricity	3.58
Poisson coefficient	0.25	σ_{b0}/σ_{c0}	1.125
Density	2.62×10^{-9} N/mm^3	K_c	0.59
Dilation angle	35°	D_c	0.75

Simulations of impact with a single insert were run to calibrate the critical damage D_c based on the removed volume from experiments, following Aldannawy et al. (2022). The critical damage D_c represents somehow the damage beyond which the rock is considered as fractured or as debris. A quarter 3D model of the setup was modelled, see Figure 2(a). Single insert impacts with impact energy of 30, 60 and 94 J were performed under 30 MPa confining pressure and a weight on bit of 2.88 kN. The volume removed was estimated by computing the volume of all elements with a damage higher than a critical value a. A value of 0.75 for the critical damage D_c was then found to provide a good fit with the experimental data, see Figure 2(b).

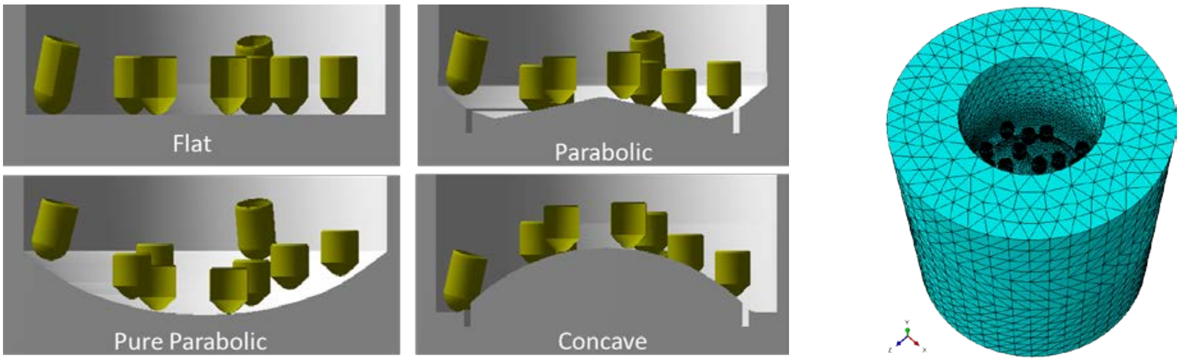


(a) (b)

Figure 2: (a) FE model of single insert impact and (b) volume removed vs impact energy (experiments and simulations).

Simulations of one impact of a 6" drill bit against the Red Bohus granite under on-site conditions were then performed using the calibrated model. The drill bit was made of 16 inserts, among which 12 had a conical shape and 4 a spherical shape; only the inserts from the drill bit were modelled. Four different profile geometries were considered: flat, concave, parabolic and pure parabolic, see Figure 3(a). The effect of a groove, supposedly generated by a high pressure water jet, was also investigated: no groove, 10 mm and 30 mm deep. The groove was 3 mm wide and had a mean diameter of 124 mm. There were altogether twelve different configurations investigated.

The inserts were modelled as rigid bodies and meshed with about 22,500 rigid elements, R3D4 and R3D3. The rock was discretized with, depending on the profile geometry, between 414,000 and 565,000 quadratic tetrahedral elements, C3D10M. In all simulations an energy impact of 1940 J was used, i.e., about 120 J per insert. The inserts were given a total mass of 21 kg and an initial velocity of 13.6 m/s. A constant weight-on-bit of 15 kN was applied on the inserts. The rock volume modelled was cylindrical in shape with an external diameter of 300 mm and a height of 300 mm. Figure 3(b) shows a typical finite element model, here for a concave profile without groove. A constant pressure of 100 MPa was set on the external horizontal and vertical walls while a constant pressure at the bottom-hole, inner walls and groove walls was set to 40 MPa. An internal stress of 100 MPa was initially set to the rock. The bottom face of the volume was fully constrained and the inserts were constrained to move only vertically.

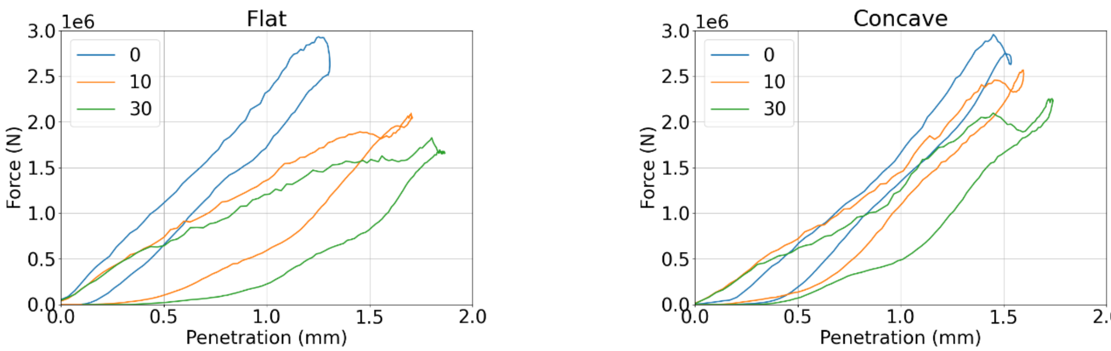


(a) (b)

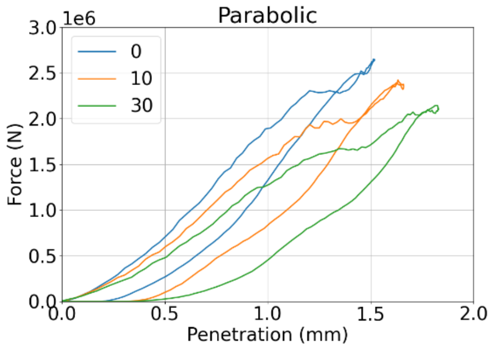
Figure 3: (a) Profile geometries investigated and (b) example of finite element model.

4. RESULTS AND DISCUSSION

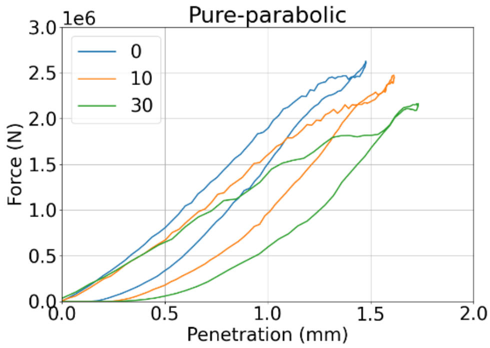
Figure 4 shows the force vs penetration curves for each profile and groove depth. Both force and penetration are collected from the bit. The shape of the curves is affected by stress waves propagating in the medium. All configurations generate maximum impact loads from about 1800 to 3000 kN and maximum penetrations from 1.3 (flat profile without groove) to 1.9 (flat profile with groove depth of 30 mm) mm. Increasing the depth of the groove decreases the impact load and increases the penetration at the same time. However, the effect of groove depth on penetration is the least for the concave profile. Similarly, increasing the groove depth increases the permanent penetration, i.e., penetration after unloading, for all profiles. The largest decrease in impact load, due to having a groove vs no groove, is observed for the flat profile; the least decrease is seen for the parabolic-type profiles. Similarly, the largest increase in penetration due to the groove is observed for the flat profile and the least increase is seen for the concave profile.



(a) (b)



(c)

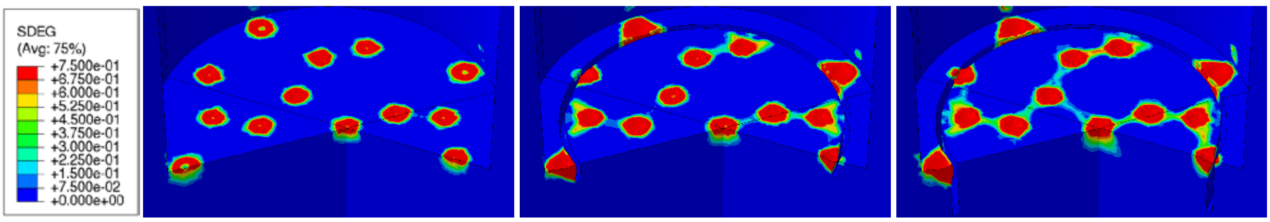


(d)

Figure 4: Force-penetration curves for (a) flat, (b) concave, (c) parabolic and (d) pure parabolic profile, for different groove depths (in mm).

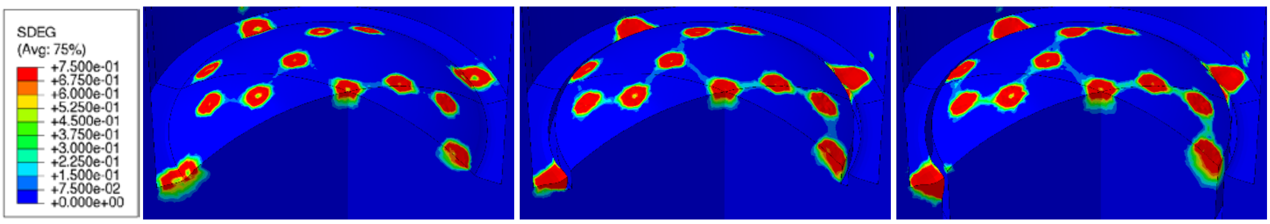
Figure 5, Figure 6, Figure 7 and Figure 8 show contour plots for flat, concave, parabolic and pure-parabolic profiles, respectively, at the end of the unloading; the cut-off for the damage in the plots is 0.75, which is the calibrated critical damage. At first, we focus on the effect of the groove on the distribution of damage around and especially between indents. These figures show that increasing the groove depth increases the damage below, around and between indents. It can be seen that even without any groove, there is more damage between indents for the concave profile than for the other profiles. When the groove is 10 mm deep, the highest damage between indents is observed for the concave profile and, to a lesser extent, the flat and parabolic profiles; no noticeable damage is observed for the pure-parabolic profile. However, when the groove is 30 mm deep, damage between the indents is increased for all profiles but is largest for the flat and concave profiles. Although not shown here, it is observed that the tensile damage around and between the indents is higher with a groove than with none. This is attributed to a stress release effect induced by the groove. Furthermore, the deeper the groove the larger the stress release. It is worth noting that the occurrence of damage between indents promotes chipping; therefore the higher and the deeper this damage, the larger would chipping be.

We focus now on the interaction between groove and inserts located near the groove. The figures show that the extent of damage higher than 0.75 (red spots) in the central zone of the rock, i.e., away from the groove, is little affected by the presence of the groove. However, in the periphery zone, i.e., near the groove, there is an increase of damage and extent of damage (size and volume of the red spots) of the indents near the groove (compare figures (e) and (f) with (d)); this is particularly seen for the flat and concave profiles. This is again believed to be due to the stress release effect mentioned above.



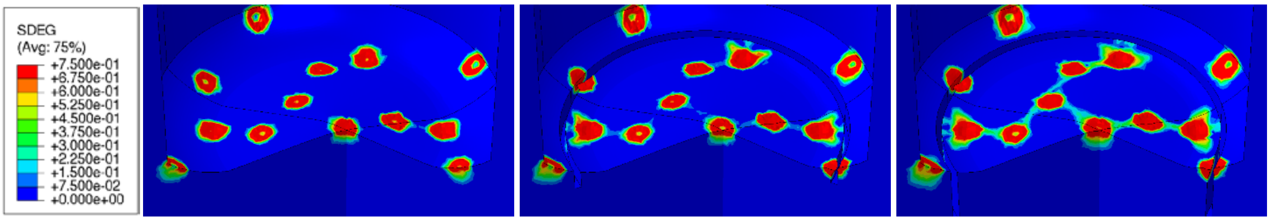
(a) (b) (c)

Figure 5: Contour plots of accumulated damage for flat profile with (a) 0, (b) 10 and (c) 30 mm deep groove.



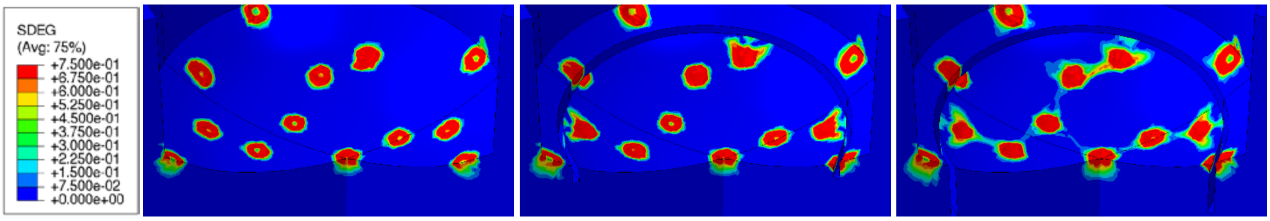
(a) (b) (c)

Figure 6: Contour plots of accumulated damage for concave profile with (a) 0, (b) 10 and (c) 30 mm deep groove.



(a) (b) (c)

Figure 7: Contour plots of accumulated damage for parabolic profile with (a) 0, (b) 10 and (c) 30 mm deep groove.



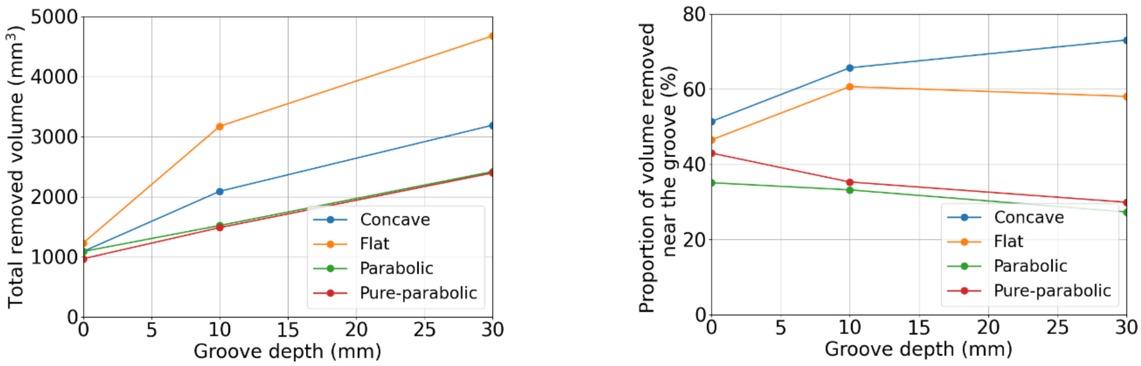
(a) (b) (c)

Figure 8: Contour plots of accumulated damage for pure-parabolic profile with (a) 0, (b) 10 and (c) 30 mm deep groove.

The above observations seem to indicate that the volume of rock fractured or removed increases with the depth of the groove, and that rock fracture would be larger at the periphery zone than the central zone. Therefore, the volume fractured or removed, defined as the volume of elements which for the damage is higher than the critical damage D_c of 0.75, has been computed for each configuration.

Figure 9(a) shows the total volume removed, i.e., for all elements in the rock fulfilling $D_c \geq 0.75$. It clearly appears that increasing the groove depth increases the volume removed as suggested previously. It can be also seen that there is a strong effect of the shape of the profile, where the flat and concave profiles produce the largest volume removed. However, both profile and groove depth have a limited effect for the parabolic-type profiles.

Figure 9(b) shows the proportion of volume removed by the inserts (7 of them) near the groove, i.e., inserts located on either side of the groove. While about 40 to 50% of the total volume removed is attributed to those inserts when there is no groove, this amounts to about 60 to 70% for the flat and concave profiles. However, this proportion decreases for the parabolic-type profiles. This indicates that the presence of a groove is beneficial for the concave and flat, although a slight decrease is observed for the 30 mm deep groove, profiles but not for the parabolic and pure-parabolic profiles.



(a) (b)

Figure 9: (a) Total volume removed and (b) volume removed by the inserts near the groove, for each profile and for different groove depths.

5. CONCLUSION

3D parametric FE simulations of bit-rock interaction have been performed in order to assess the influence of various bit designs and bottom hole profiles on the rock breaking efficiency. The rock, a Red Bohus granite, was modelled using a continuum, plasticity-based, damage model calibrated using uniaxial and triaxial experimental test data. Four different bit geometries were modelled (flat, parabolic, pure-parabolic and concave) with their associated bottom hole profiles, and three groove depths (0, 10, 30 mm) were considered. The results obtained showed that the presence of the groove affects both impact load and penetration. The groove also affects the amount and extent of damage below, around and between indents, especially near the groove, as well as the total volume fractured, or removed. It is finally found that the presence of a groove is significantly beneficial only for the concave and flat profiles.

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