ARMA 23-0780

Influencing Factors in Rock Cutting Using High Pressure Water Jets Under Submerged Downhole Conditions

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ABSTRACT: Utilizing deep geothermal energy is an important factor in successful transition to a clean, affordable and non-intermittent source of energy. However, high costs due to low drilling performance is a showstopper in scaling geothermal energy. It has been noted that there is a significant drop in the rate of penetration (ROP) in hard crystalline granite rocks averaging between 1-2m/h. These hard rocks are found at depths greater than 4 km and increasing the ROP by a factor of 4 could reduce the drilling costs by 65%. In the framework of ORCHYD (Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in Deep Geothermal Drilling) project, we investigate ways to reduce the confining stresses of the underground rock so as the energy required to break the rock will be significantly lower and thus, increasing the ROP. A high-pressure water jet (HPWJ) of up to 250 MPa is generated in the bottomhole conditions to create peripheral groove of a few millimeters to release the rock layer from the surrounding stress regimes – reducing the energy required to break the rock using percussion drilling. Nevertheless, generating the required energy for rock slotting depends on several factors such as nozzle type, output pressure and confining pressure. In this paper, we investigate experimentally the influencing factors of HPWJ for rock slotting in bottomhole drilling conditions.

1 INTRODUCTION

Scaling geothermal energy is a potential solution in serving our transition needs to a clean, sustainable, non-intermittent and renewable energy source. However, to effectively utilize this energy source, it is required to drill deeper wellbores than previously done in the oil and gas industry. On an average, it is required to drill to depths greater than 4 km to achieve a temperature of above 150 °C in the reservoir rocks to be useful for electricity generation. With nearly 50% contribution to the geothermal exploration, very high drilling costs is a showstopper in making geothermal truly scalable. A majority of the drilling performance, measured as rate of penetration (ROP) in hard crystalline rocks found at such depths is $1 - 2$ m/h, e.g., Soultz-sous-Forêts in France (Baujard et al., 2017), and our study shows that increasing ROP by a factor of 4 can reduce the total drilling costs by up to 65%.

It is known that, in general, the confining stress regimes around the underground rock increases with depth. This increase in confining stresses is a major factor contributing to the reduction of drilling performances at greater depths, simply due to the increase in energy required to break the rocks. In the ORCHYD project, we utilize a stress release effect by creating peripheral grooves using high-pressure water jet (HPWJ) to reduce the confining stresses of the underground rock so as the energy required to break the rock will be significantly lower and thus, increasing the ROP. In this project, a fully fluid-driven prototype combining a down the hole (DTH) mud hammer and a high-pressure water jet (HPWJ) will be developed. The influence of creating peripheral grooves using HPWJ of up to 250 MPa in the underground conditions, in reducing the confining stresses of the rock will be studied and measured as ROP at a laboratory scale drilling rig.

The two mature technologies: rock slotting using HPWJ and percussion drilling using DTH hammer were studied earlier. Recent developments in the DTH hammer and percussive drill bit design have shown increase in the ROP (Van Hung et al. (2016); Gerbaud et al. (2018); Souchal et al. (2017)) but the studies on the effect of high pressure water jetting and the factors influencing the destruction of the rock were restricted to atmospheric pressure only. Stoxreiter et al. (2018) performed circular cuts with pure water on 6 rocks with jet pressures of 400 MPa. Harris and Mellor (1974) made linear cutting tests on 3 different rocks with a pure water jet. Karakurt et al. (2012) performed cutting tests with an abrasive water jet. There are also many experimental results for the analysis of the cutting performance of high-pressure water jets in submerged environments with low confining pressures where the focus is on the generation of cavitation at the nozzle outlet to improve cutting performance (Liao et al. (2020)). However, only a few experimental studies are available under high confinement pressures up to 45 MPa (e.g., Reichman (1980); Kolle (1987), or Stoxreiter et al. (2019)). Through this experimental study, we aim to provide better understanding of the operations of a HPWJ under submerged pressure conditions of up to 50 MPa.

2 STRESS RELEASE

In general, the confining stresses increase over depth due to the increase in mere weight of the rock overlaying a given rock surface. Due to the increasing overburden, the rock resistance to cutting also increases. Creating a borehole alters the stresses around the rock layer and influences the energy required to break the rock – more energy as the wellbore extends deeper. In principle, creating a peripheral groove on the rock surface shall release it from the confining stresses emulating a near-surface condition. This effect is further influenced by the profile of the bottom hole resulting from the bit profile. The stress release effect is demonstrated in Fig 1 where the mean stress concentration factor – a dimensionless factor defined as the ratio of the highest stress in that region to the reference stress – is influenced by the profile of the bit and the presence of a peripheral groove. A numerical study was conducted to study the influence of the groove depth in stress release effect. The Fig 2 shows the variation of the mean stress concentration factor as a function of the ratio groove depth to the bit diameter. For the concave bit profile, the maximum stress release is obtained at a ratio of 0.4, i.e., a groove depth of more than 5 cm. However, a groove depth of 1.5 cm already releases more than 50% of the confining stresses for a concave bit profile. In the following sections, the process of creating a groove is studied experimentally.

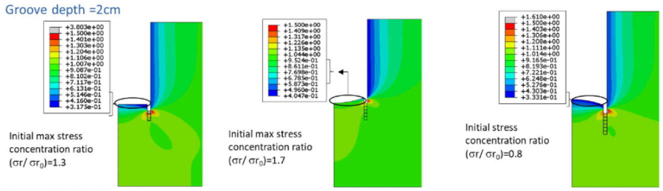


Fig. 1: Mean stress concentration factor distribution in the underground rock surface depending on the profile of the drill bit.

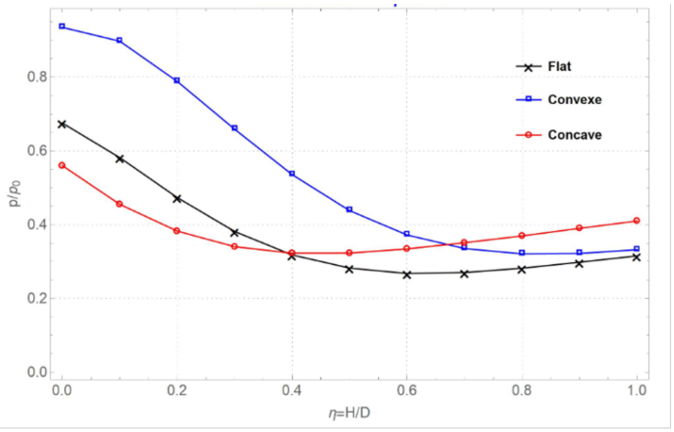


Fig. 2: Variation of the mean stress concentration factor as a function of the ratio groove depth to bit diameter.

3 EXPERIMENTAL SETUP

As seen earlier, for the stress release effect to play a role, the drill bit profile and the depth of the peripheral groove are two major influencing factors. In this work, to study the different factors that influence the depth of the peripheral groove, the experimental setup in Pau, France that was used to study the rock breakage caused by the impact of a single insert to optimize the percussion drilling process Aldannawy et al. (2022) was modified and the following subsystems were added for this study.

3.1. High-Pressure Cell

As seen from the schematic in Fig 3, the new system is composed of a high-pressure tube with a nozzle fixed at the extremity inside the cell (1) that are held in place with sealing systems. The rock (2) placed on a rotating plate inside the pressure chamber (3) that is filled with water and pressurized using a choke restriction at the flow outlet.

3.2. HPWJ System

For experimental purposes, a high-power diesel pump is used to create fluid pressures of up to 250 MPa. A high-pressure transmission line connects the pump to setup as shown in Fig 4 and is secured to a base plate hosting a rigid axial pressure line (part 1 of Fig 3 to which different nozzles can be attached. The pressure line can move axially to control the stand-off distance: the distance between the

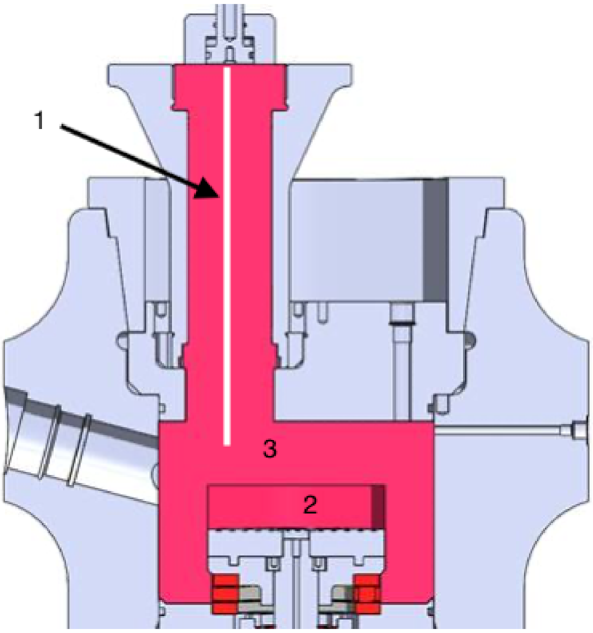


Fig. 3: Drawing of the pressure cell that include a HPWJ transmission transmission line and a rotating platform to host a block of rock.

exit of the nozzle and the surface of the rock. The high-pressure pump used is a WOMA type 250 M P18 with the following parameters: Pump power - 133 kW; Maximum pressure - 250 MPa; Maximum flow rate - 29.5 l/min; Motor type - TWD 710 V; Motor power - 168 kW; and Maximum nozzle diameter - 1.05 mm.

3.3. *Back Pressure Choke*

A spring type choke is used to hold the pressure in the chamber whose maximum operating pressure is 50 MPa. The torsional spring of the choke is screwed a priori to maintain the required pressure inside the cell. A double sieve filter was fixed to avoid choke plugging events.

3.4. *Rotation Control*

In field applications, the HPWJ will be integrated in the DTH hammers and thus rotate during the operations. To study the effect of rotation of the rock grooving process, a laser system is set up to read the position and speed of the rotation of the rock. The rotation is controlled using a separate hydraulic motor.

3.5. *Pressure Sensors*

The high-pressure pump comes with its own control system that measures the pressure and the flow rate of the pump output. Two more sensors are integrated on the experimental setup - one at the juncture of the transmission line to leading to the flowline with nozzle; another that measures the pressure inside the chamber. The data acquisition and control systems were designed using LabVIEW software.

Fig. 4: The high-pressure impact cell modified to accommodate the HPWJ experiments. The high-pressure transmission line is connect to a pump that can generate a maximum pressure of 250 MPa.

Table 1: Rock properties for Sidobre of type granodiorite.

Parameter	Value	Unit
UCS	221	MPa
Grain size (min - max)	2 - 10	mm
Density	2.65	g/cm^3
Sound velocity	3960	m/s
Porosity	0.5	%

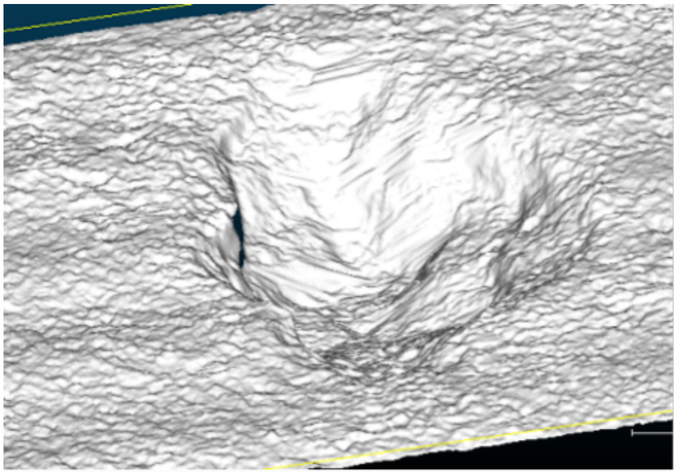
3.6. *3D Crater Scanning*

A laser scanning system was setup to scan the craters created by the impact of HPWJ. The system is controlled by a LabVIEW software routine and works on the principle of measuring the time for reflection of the laser beams. The processed data can then be used to graphically view the contours of the crater using software like CloudCompare and ParaView. An example of a crater is shown in Fig 5.

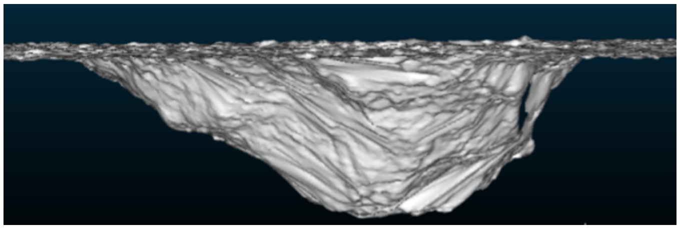
4 INFLUENCING FACTORS

The representative hard crystalline granite chosen for this study is Sidobre. The rock characteristics of Sidobre granite are listed in Table 1. The rock samples are exposed to a static feed of HPWJ and the groove depth is investigated by varying one at a time the following degrees of freedom : back pressure, injection pressure, standoff distance and exposure time, i.e., when the back pressure is varied, all other operating parameters are set constant. Here, the groove depth is measured as the maximum depth of the crater created by the HPWJ impact.

In Fig 6 the maximum groove depth achievable under the



(a) Depth perspective view of the crater.



(b) Side view of the crater.

Fig. 5: Graphical render of the crater scan data using CloudCompare.

influence of different back pressure is shown with a nozzle F1 of 1 mm diameter, a jet pressure of 240 MPa, a standoff distance of 5 mm and an exposure time of 20 s. Here, the back pressure directly translates to the depth of operation of the HPWJ, i.e., a back pressure of 40 MPa is equivalent to operating the HPWJ at a depth of 4 km. It can be noted that, while all other parameters are set constant, the grooves are shallower with the increase in depth of the drilling operation.

In Fig 7, the influence of the injection pressure on the groove depth is shown (nozzle F1 of 1 mm diameter, back pressure of 20 MPa, standoff distance of 5 mm and an exposure time of 20 s). The results are obvious, i.e., higher the injection pressure, higher is the energy available to break the rock and thus the creation of a deeper groove. It is important to note that 250 MPa is the highest operating pressure of the pump available at the laboratory facility in Pau, France and achieving such high pressure in the downhole environment can be challenging.

In Fig 8, the effect of the standoff distance, i.e., the distance between the outlet of the jet and the rock surface on the groove depth is shown (nozzle F1 of 1 mm diameter, back pressure of 20 MPa, injection pressure of 240 MPa and an exposure time of 20 s). The lower the standoff distance, the closer is the jet to the rock and effectively less

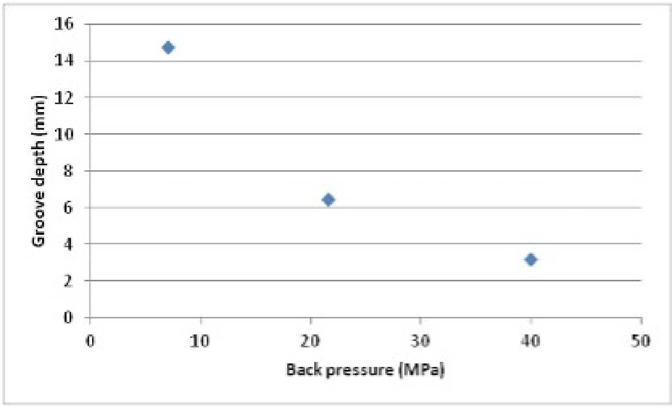


Fig. 6: Effect of back pressure on the groove depth.

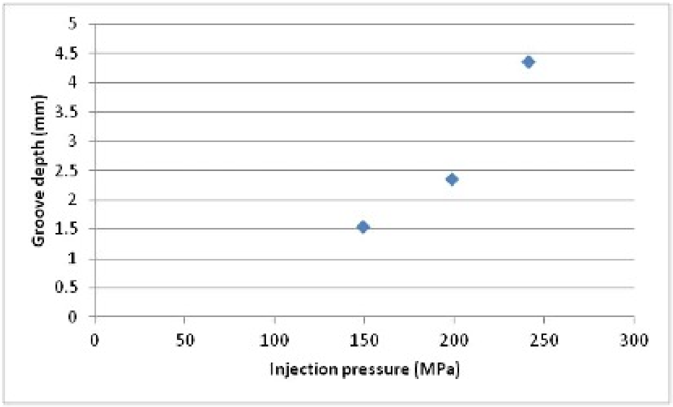


Fig. 7: Effect of injection pressure on the groove depth.

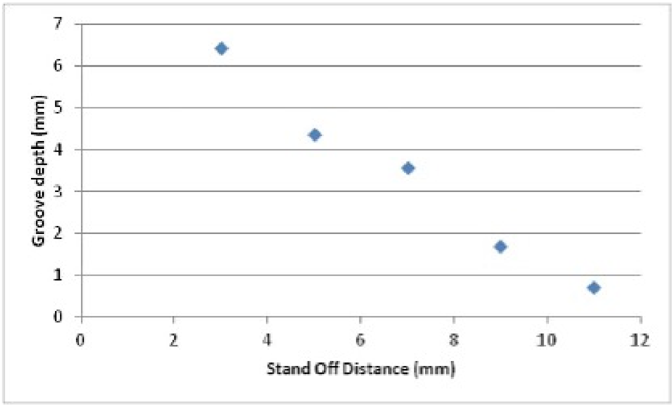


Fig. 8: Effect of standoff distance on the groove depth.

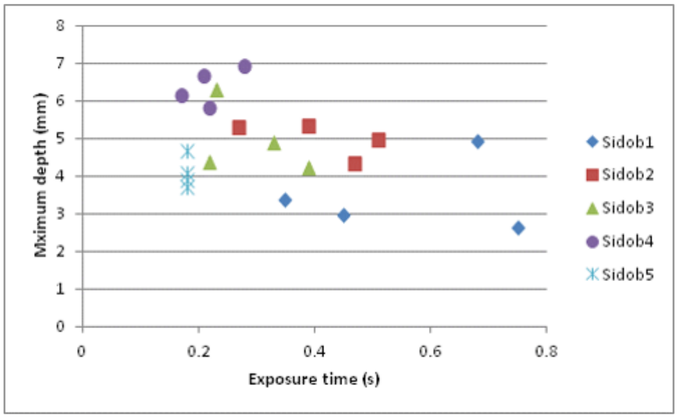


Fig. 9: Effect of exposure time to the HPWJ on the groove depth.

dissipation of energy during the jetting process. The results clearly show that a deeper groove is achieved when the standoff distance is lower. They are also consistent with the conclusion that the bottom of the hole eroded by the jet does not significantly exceed the distance from the nozzle over which the jet core is at full strength (i.e., 7-10 times the nozzle diameter). However, one of the limiting parameters in such implementation is the design requirements and the practicality of a drill bit that can accommodate it.

To obtain statistical accuracy, the test with a setpoint for the back pressure of 20 MPa, injection pressure of 240 MPa, and standoff distance of 3 mm was repeated over a few times and are shown in Fig 9. The dispersion in the test results can be attributed mainly to two reasons. First, the rock heterogeneity – different grains of varying sizes were exposed under the jet for each new test leading to a different sequence of grain breakage/ detachment from the rock surface. Second, physical constraints in controlling the exposure time – the exposure time of the HPWJ was manually controlled leading to experimental errors.

5 CONCLUSIONS

The objective of this study was to carry out an experimental study of rock cutting by high-pressure water jetting to understand the influence of operating and design parameters (type of nozzle, nozzle diameter, injection pressure, rotation speed) and of the in-situ environment (type of rock, back pressure). The various tests carried out showed that the depth of the groove hardly reached a depth greater than 10 mm and that the back pressure had a significant negative effect on the depth. It was also possible to observe that the groove cut could lead to an improvement in performance with a groove width well beyond the impact zone. Due to the heterogeneity of the rocks, the groove depths varied while repeating the tests of same conditions for a given sample. Finally, we can also consider that the results obtained correspond to the minimum value that can be obtained in real conditions. It is very likely that the jet performance varies a lot in the experimental device where the fluid is injected at a flow rate of 30 l/min in a volume whose pressure is controlled by opening/closing of a spring-actuated choke - leading to variations in the confining pressure. Future tests on the drill rig should clarify this hypothesis as the confining pressure will be controlled with a fluid flowing at a rate of 600 l/min with the annular volume of the wellbore much higher than the experimental cell volume providing a stable back pressure to the HPWJ system.

ACKNOWLEDGEMENTS

This project was funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101006752.

Authors would like to thank Jorge Aising for his assistance with CAD diagrams and Eric Phelipot for his assistance in the experiments.

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