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Preliminary experimental validation of the improved ROP using hammer and High Pressure Water Jet

Gerbaud L., Cazenave F., Velmurugan N., Sellami H., Jahangir E.

laurent.gerbaud@minesparis.psl.eu

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ABSTRACT

Increasing drilling speeds to reduce drastically the costs is the main challenge to promote deep geothermal systems. Traditional rotary techniques show limitations in drilling speed on very hard deep crystalline rocks with low ROP and/or high wear level. This is the challenge pursued by ORCHYD, using the combination of high-pressure water jetting (HPWJ) and percussion to break the rock. For this, the stress release effect is exploited by combining these two techniques of rock breakage. A peripheral groove is created by the rotating jet at the bit, reducing the stress concentration at the center, reducing the energy required to crush the rock in the center by the hammer action.

Two test experimental devices have been adapted to emulate the realistic down-hole pressure conditions on a hard rock sample. A high pressure cell to analyze at the nozzle or insert level where we can use the percussion or the jet to cut the rock. A vertical drilling test rig to analyze drilling behavior using a combination of high pressure water jet slotting and percussion action at drill bit scale and under realistic drilling conditions. The hammer is fluid driven and thus, appropriate hydrostatic and confining pressures are applied during the operation. Parameters investigated include chamber (bottom hole) pressure, nozzle orifice diameter, stand-off distance, rotation rate as well as in-situ stress and pore pressure conditions. Experimental results are analyzed in terms of rock breakage mechanisms, depth and shape of the groove and rate of penetration with and without jetting, in order to assess the efficiency of the combined tool.

1. INTRODUCTION

Deep geothermal energy is a key development gateway for energy security in the world. Geothermal electricity production is also a powerful lever for heat energy recovery for rich and poor economies alike, with high and constantly growing energy needs. This is reflected in the development of EGS (Enhanced Geothermal System) which often combines both production of electricity and heat at the power plant. In the field of geothermal energy, drilling operations are an important part of the project cost. They represent 40% of the total cost, which reaches 15 M€ for a 3 km well, knowing that the target depths are between 3 and 5 km (Angelone (2014)).

The cost of deep geothermal drilling is influenced by the challenge of penetration speed, to drill through tough formations using conventional rotary drilling bits like roller cone and PDC bits with a satisfactory rate of penetration (ROP). The study of deep drilling has been a topic of extensive research over the past 60 years. The primary focus has been to improve the rate of penetration (ROP) in oil and gas formations by identifying mechanisms restricting the optimal performance and developing solutions to overcome them. Researchers have investigated various factors affecting the drilling process, including static and dynamic chip hold down; balling-up of the hole bottom and drill bit; pore pressure and mud filtration; overburden pressure, mud pressure, and formation pressure; bit size and hydraulics. The design of drilling bits has improved greatly in the past 20 years, thanks to advancements in cutter material, shape, and setup, as well as the changes in bit geometry and profile. Unfortunately, penetration rates in deep, hard formations such as granite remain low and are often below 2-3 m/h (Cardoe et al. (2021), Baujard et al (2017)), mainly because the rock subject to the constraints of the drilled depth and are not economically drillable. New and innovative drilling techniques must therefore be found. The approach chosen in the ORCHYD project consists of combining percussion drilling with peripheral groove-cutting with a high-pressure water jet to relieve the stresses at the face of the drill bit. Indeed, it has been shown that the excavation of a hole redistributes the stresses and it is possible to release the stresses to improve the penetration speeds (Qin et al (2019, Roohi et al (2022)).

Down-the-hole (DTH) percussive drilling is a technology that consists in applying a series of impacts via an oscillatory movement of a piston that impacts a drill bit at a frequency of 20–30 Hz at a velocity of 1–10 m/s (Haimson 1966), leading to rock fragmentation by compressive and tensile forces under the drill bit (Hartman 1959; Lindqvist et al. 1984; Hustrulid and Fairhurst 1972; Mishnaevsky 1995). This mechanism is ensured by the drill bit buttons, also called inserts, which are in contact with the rock surface. At each impact, compressive waves travel through the drill bit down to the rock material, which enables the bit penetration by indentation of the inserts into the rock (Hartman 1959). Song (2021) focused on the influence of WOB and showed that an optimal WOB can be applied to increase the ROP. New developments in DTH hamer and percussive drill bit design for deep percussion drilling in crystalline rocks such as granite have increased drilling performance and speed (Nguyen et al (2016), Souchal et al (2017), Gerbaud et al (2018))

Jet-assisted rotary drilling (JARD) is a drilling technique that uses high-pressure fluid jets to enhance the rate of penetration (ROP) and improve the overall efficiency of the drilling process. JARD has been used in various drilling applications, including geothermal, oil and gas, and mining operations. Guan et al (2014) improved by 40% the ROP using hydraulic pulsating jet obtained by the transformation of drill string vibration. Lu et al (2012) showed that with the assistance of abrasive water jet, the drilling depth has increased by about 63%, the thrust force and torque have reduced by about 15% and 20% respectively, and the bit wear has been reduced significantly. JARD has the potential to significantly enhance the ROP in deep drilling operations and improve the efficiency and cost-effectiveness of the drilling process. However, further research is needed to fully understand the advantages and limitations of JARD and to optimize its application in different drilling scenarios.

Despite the vast amount of literature on drilling processes, there is limited information on laboratory experiments on high-pressure jet-assisted drilling, particularly in full-scale. The potential of high-pressure jet-assisted roller cone bits was demonstrated in a comprehensive laboratory and field testing research study in the 1990s in Kolle et al (1991) and Veenhuizen et al (1997). Stoxreiter (2019) performed experiments of high pressure jet assisted rotary drilling with a roller cone in hard-to-drill granite (meaning low ROP value during drilling) and showed an increase of the ROP by a factor of more than 1.7 compared to the performance without JARD.

Hence, the present paper aims at the laboratory demonstration of a how performance can be improved by combining high pressure jet and percussive drilling in crystalline rock. The present study was performed with a commercial percussive drilling system where the high pressure water jet line was added to the bit periphery. After showing the stress distribution with a peripheral groove, the effect of the high pressure water jet on crystalline rock slotting has been studied. Thanks to these tests, a jetting configuration has been selected and duplicated to the drill bit set up. The performance demonstration of this new drilling technique highlights the step change in term of hard rock drilling. Thanks to the measured and monitored drilling conditions in combination with the almost perfectly homogenous rock samples, with its mechanical and physical properties determined in detail, full-scale experiments provided the ideal environment to validate the presented concept and to identify potential improvements.

2. STRESS RELEASE EFFECT

It is known that, in general, the confining stresses increase over depth due to the mere weight of the rock overlaying a given rock surface. It is also well known that rock resistance to cutting increase with confining stresses. 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 ORCHYD project, we aim at exploiting the principle that 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 induced by the bit profile and the cutter lay out. This principle is demonstrated in Figure 1 which presents the radial stress concentration defined as the ratio between the initial stress and the stress after drilling the hole and the peripheral groove. For a conventional drilling bit, with a convex profile, there is a stress concentration at the periphery and a radial stress at the working face equal or close to the initial stress with a concentration factor close to 1 (middle figure). On the other hand, if we consider a flat bit and a 2 cm deep groove, we can observe two things: (1) the stress concentration is pushed back to the bottom of the groove in the periphery, (2) a stress concentration factor of between 0.5 and 0.6 over almost the entire cutting interface. If we now consider the concave profile (figure on the right), we have an amplification of this phenomenon of stress relaxation at the cutting face with a concentration factor of between 0.3 and 04. A reduction in the stress level at the bit-rock interface of more than 60% can therefore be achieved by combining a concave profile with the digging of a 2 m deep groove at the periphery.

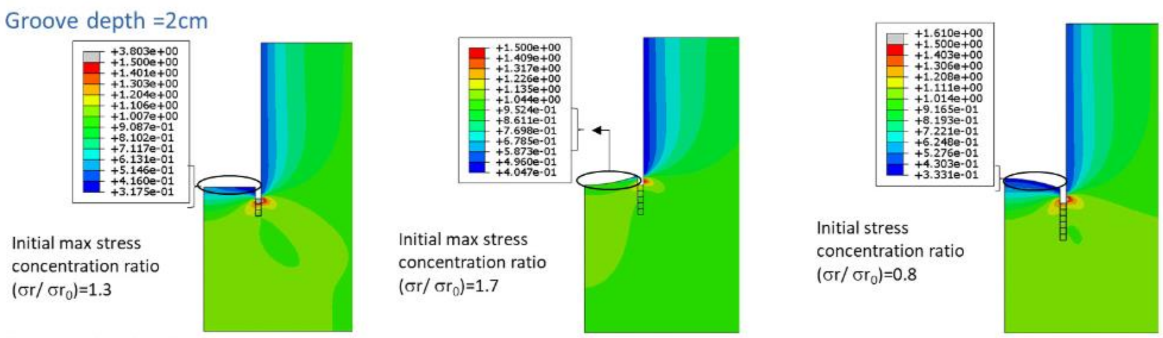

Figure 1: Mean stress concentration factor distribution in the underground rock surface depending on the profile of the drill bit

Another conclusion of the theoretical study conducted in the framework of the ORCHYD project is that stress release effect is enhanced with deep peripheral groove. The Figure 2 illustrates this with the evolution of the reduction of the mean stress concentration factor at the bit centre with the depth of the groove H expressed as a ratio of the diameter of the bit D. It can be seen that, for the concave bit profile, the maximum stress release is obtained at a ratio of 0.4 i.e. more than 5 cm. But, it can also be observed that the stress release is greater than 50% for a groove depth of 1.5 cm for a concave profile.

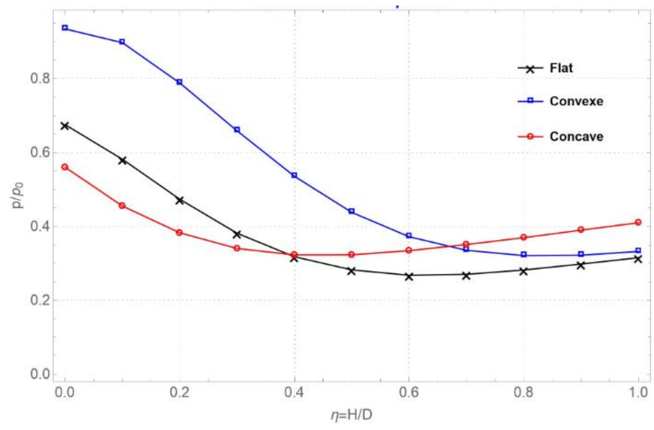

Figure 2: Stress release using mean stress concentration factor

Creating a deep groove is crucial to optimise the stress release and increase the bit ROP but it is also challenging to create such deep peripheral grooves in the downhole conditions – several phenomena including high hydraulic pressure (due to the fluid circulation in the annular column of the wellbore) and stand-off distance (the distance between the exit of the HPWJ and the rock surface) are in play. Thus, it is necessary to study the influencing parameters and study them at the laboratory scale to design the prototype to deliver this effect during percussive drilling.

3. ELEMENTARY HIGH PRESSURE CELL

The performance of a drilling bit is directly related to its design and the state of rock stress at the bit rock interface. A percussive drilling bit consists of a set of cutting elements called inserts that are in contact with the rock and transmit the compression wave generated by the impact of the hammer's piston on the drilling bit. The shape of the insert as well as the stress state of the rock and the operating parameters play an important role in the performance. Similarly, the depth of the peripheral groove is a key element in the success of the new technology as it will reduce stresses at the bit rock interface, serve as a free surface for the reflection of compression waves in the rock during percussion and as a clearing surface for crack propagation. High-pressure water jet cutting in a submerged environment is strongly influenced by the operating conditions but also by the type of jet, the travel speed, and the confining stresses. Therefore, in order to quantify the cutting performance of the high-pressure water jet in an environment representative of pressure conditions at several thousand meters depth, an existing drilling cell was modified. The following section presents the cell as it was used for the percussion tests and how it was adapted to conduct the high pressure waterjet cutting tests.

3.1 Experimental Setup

3.1.1 Description

A rock sample is placed on a turntable inside a cell where the confining pressure is controlled to up to 50 MPa (Figure 3). The insert, attached to the end of a bit, is held in contact with the rock by a constant pressure of nitrogen – emulating weight on bit (WOB). A 13.8 kg piston dropped from a given height impacts the end of the bit located outside the cell. The compression wave is then transmitted to the insert and then to the rock. Once the impact has been made, the rock is extracted from the cell and the shape of the impact (Figure 4) is measured using a 3D scanner to determine the volume of the impact and the depth of the crater. Further description can be found in Aldannawy et al (2022).

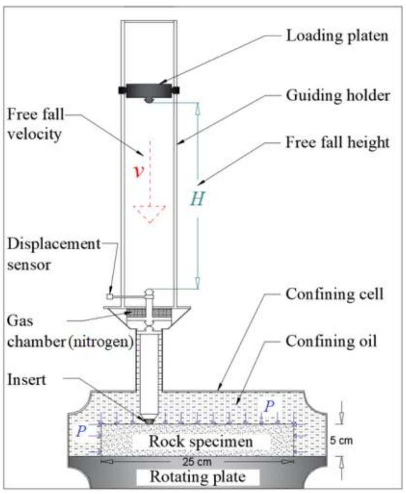

Figure 3: schematic of the pressurized drop cell

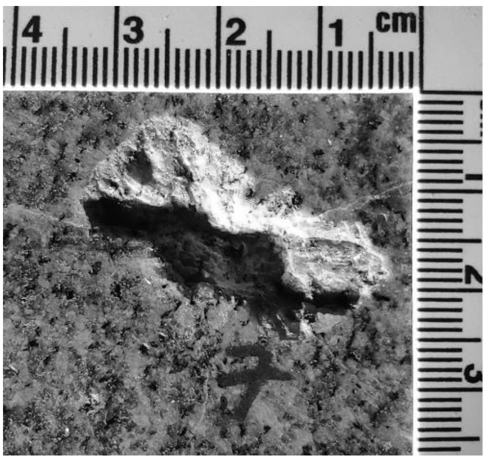

Figure 4: Photo of an impact result on Kuru Grey granite

3.1.2 Modifications for High Pressure Water Jet test

In order to realize HPWJ slotting test, several modifications were made on the experimental device describe in the above section. The system to maintain the insert was removed and changed to accommodate the high pressure line to bring the water jet close to the rock. The new system is composed of a high-pressure tube with a nozzle fixed at the extremity on the inside of the cell with two sealing systems at the top and the bottom. A high-power diesel pump WOMA type 250 M P18 is used to create fluid pressures of up to 250 MPa. A high-pressure transmission line is used to channel the flow to the experimental setup. The transmission line is secured to a base plate hosting a rigid axial pressure line to which different nozzles can be attached. This pressure line has a degree of freedom to move axially thus controlling the stand-off distance (distance between the nozzle outlet and the rock). This is crucial as the hydraulic power of a jet drops drastically above a stand-off distance 6.57 times the diameter of the nozzle (Kolle (1987)).

Figure 5: The high pressure impact cell modified to accommodate the high pressure water jetting experiments.

Though the cell can hold up to a pressure of 50 MPa, it was in static conditions, i.e., the cell was pressurized using a hydraulic pump. However, it is necessary to have a choke to control the pressure when there is fluid flowing. A spring type choke was used in this system. The torsional spring can be screwed a priori to maintain the required tension in the spring system and thus the pressure inside the cell. A high-pressure transmission line connects the exit of the pressure cell to the choke. The rock cuttings plugging the choke were common. Thus, a double sieve filter was fixed to hold back the rock particles from entering the high-pressure line leading to the choke.

3.2 Results and discussion

In the first phase of the experiments, the rock samples are held stationary under the impact of the HPWJ to study the effect of back pressure, injection pressure, standoff distance, and exposure time. Sidobre granite was used as the reference rock in these tests (Table 1). The figure shows a crater obtained in a non traversing test and its reconstruction with CloudCompare after the 3D scan. It can be seen that the shape is conical rather than a deep, narrow groove. We therefore have a lateral rupture as observed by Stoxreiter et al. As groove depth is the influencing parameter in the stress release process, it is chosen as the control variable to understand the influence of other parameters related to the HPWJ. Here, the groove depth is measured as the maximum depth of the crater created by the HPWJ impact.

Tableau 1: Mechanical characteristics of Sidobre Granite

Name of Rock	**Type of Rock**	**UCS (MPa)**	**UTS (MPa)**	**Grain size min-max (mm)**	**Density (gr/cm^3)**	**Sound velocity (m/s)**	**Porosity (%)**
Sidobre	Granodiorite	221	8	2 – 10 mm	2.65	3960	0.5

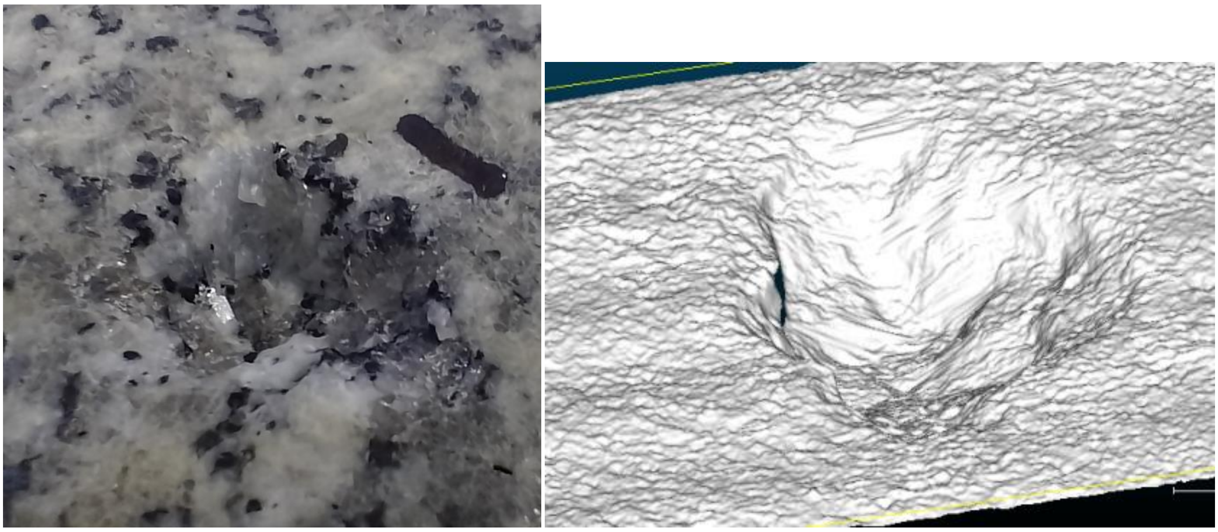

Figure 6: Crater after 250 MPa jetting under 20 MPa of confining pressure and its reconstruction with CloudCompare in non-traversing test

The effect of the stand-off distance, defined as the distance between the nozzle outlet and the rock surface, can be observed (figure 7). The results obtained by several authors (Kolle (1987), Stoxreiter et al (2018), Hlavac et al (2001), Hlavac et al (2005) ..) such as the decrease in the depth of the groove when the stand-off distance increases can be observed in these experiments as well. It can also be noted that the sum of the stand-off distance and the depth of the groove increases as the stand-off distance increases. This implies that the efficiency is maintained longer in water than in rock and that even if the stand off distance is increased, there will not result in a same decrease in the depth cut. It is also observed that the jet remains effective up to 10 to 12 times the nozzle diameter, beyond the zone where the jet remains consistent with a pressure equal to the outlet pressure, i.e. in the zone of 0 to 7 times the noozle diameter.

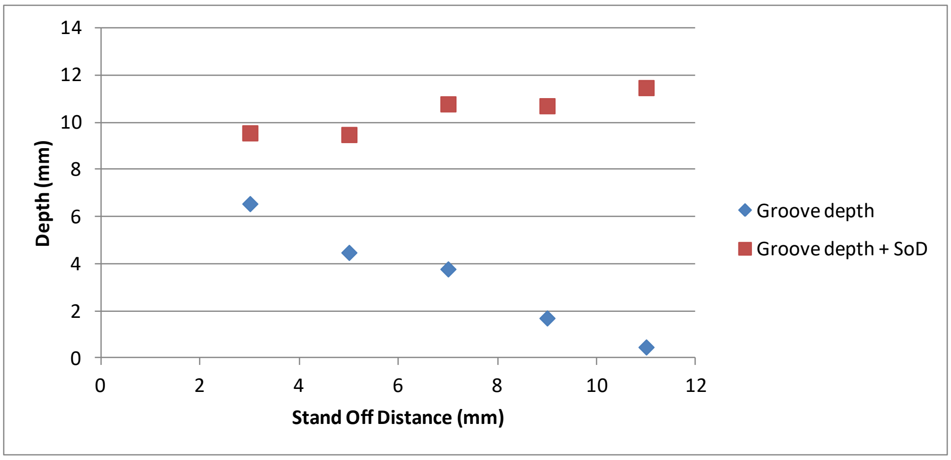

Figure 7: Groove depth and cumulative distance with stand off distance versus stand off distance

In the next phase of the experiments, the influencing parameters were studied under the influence of the rotation of the rock sample. A full rotation of the HPWJ was conducted to understand the grooving process during the drilling action. Similar to the non-traversing (i.e., no rotation) experiments, the influence of various parameters were studied while the rock is rotating. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a Sidobre rock sample that was placed under the impact of the HPWJ during rotation. This rock was scanned using the laser setup and then graphically viewed using ParaView to calculate the groove characteristics (depth, width and cross area) along the circumference of the rock. A sample result is shown in Figure 8. We observed a large fluctuation of the groove depth between 0 to 6 mm (the peak depth at 8 mm is the starting point and is obtained before rotation when the cell is pressurised at the beginning of the jetting). This large fluctuation can be explained by the high heterogeneity of the rock (the impact zone of the jet is about 1mm in diameter while the grain size is 4 to 10mm) and also by the turbulence inside the cell (the jet is used to pressurise the cell with a small volume of water and the choke opens and closes to maintain a constant back pressure).

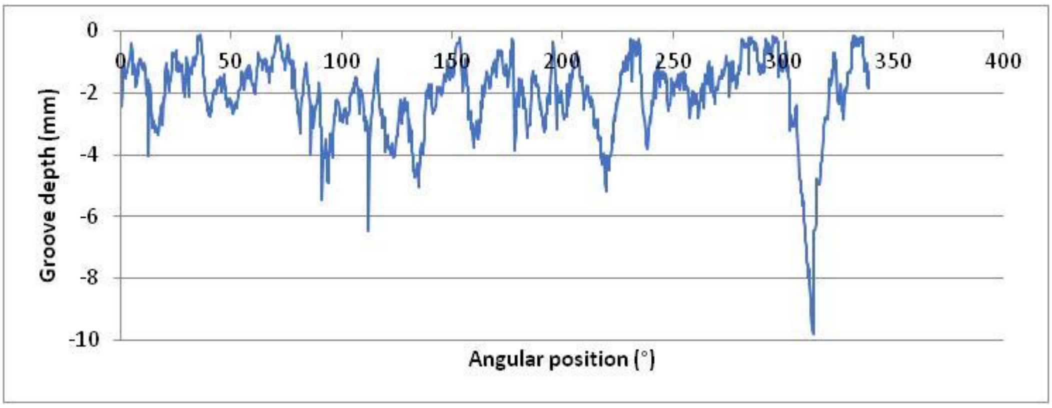

Figure 8: Groove depth with respect to the angular position of the rock subjected to HPWJ during rotation

4. VERTICAL DRILLING TEST BENCH

4.1 Experimental Setup

4.1.1 Description

The Mines Paris drilling bench allows testing of full-scale drill bits under deep drilling conditions while controlling the major variables of the drilling process. The rock sample is held in a pressure cell (Figure 9) within which constant overburden pressure, confining pressure and pore pressure are applied to the rock sample. Weight On Bit (WOB) up to 245 kN can be applied to the drill bit by means of two lateral pistons and the rotation of the drill bit (up to 1000 RPM) is generated by a DC electric motor placed on the drilling floor of the bench. The motor is connected to the drill shaft by a gearbox. The drilling mud of any type (water, WBM, …) is injected at the drill bit through the drill pipe using a Gardner-Denver PL7 pump. The tests could be performed with WOB or ROP control.

During the drilling tests, the different pressures, temperature, bit torque and ROP are continuously recorded. The data are recorded at 200 Hz sampling rate and are stored in ASCII file.

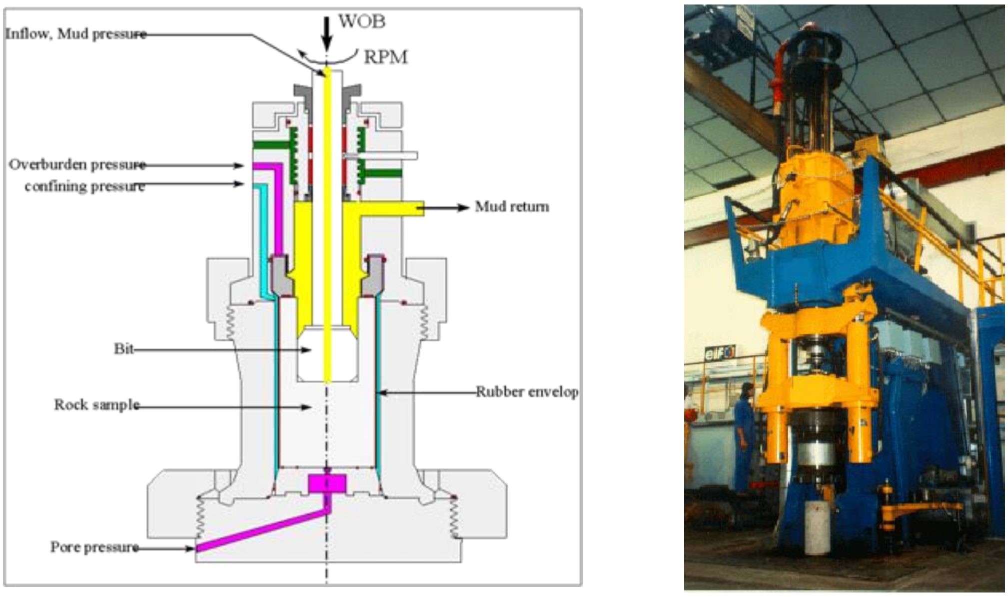

Figure 9: Mines Paris drilling test bench

4.1.2 Modifications for High Pressure Water Jet test

A high-pressure (HP) line was added to the drilling bench co connect the HP pump to the HP nozzle fixed on the drill bit. This transmission line includes a swivel connection system with the top of the drill shaft including several complex sealing systems ensuring the HP jet supply as well as allowing the free rotation (tubes, tees, bends, swivels, sensors, ...). Inside the drill shaft, the HP tubes connecting the swivel to the drill bit were made of sleeves (Figure 10). The high pressure was provided by a WOMA pump type 250 M P18, with a maximum flow rate of 30 L/min at 250. The pressure loss along the HP line is about 10 MPa for the maximum pump operating pressure.

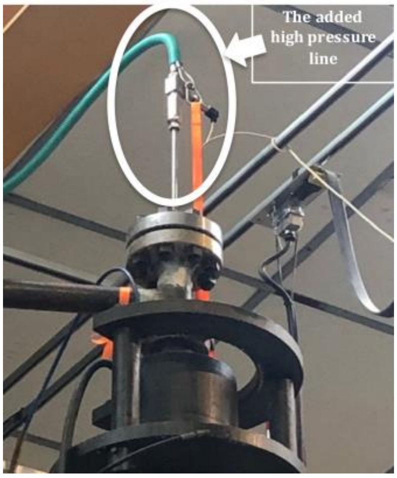

Figure 10: Modified swivel to allow High Pressure Water line on rotating drillstring

Figure 11: HP line at the swivel

4.1.3 Testing procedure

The drilling bit used is a 6’’ hammer manufactured by Drillstar Industries, partner of the *ORCHYD* project, especially designed for the needs of the laboratory study (figure 6). It is equipped with both dome and conical inserts, and includes a conventional flow system of drilling fluid through four low-pressure nozzles to cool and clean the bit and to evacuate cuttings, as well as a high-pressure system with a pressure of up to 220 MPa, projecting the fluid through a single high-pressure nozzle of 1 mm diameter attached to the bit in order to slot a peripheral groove. The stand-off distance for the extended nozzle was set constant at the closest possible value, around 3-4 mm, for all experiments.

Figure 12: Modified hammer drill bit with HPWJ nozzle

Given the limitations of the test rig, the simulated depth was 2000 m, i.e. a horizontal and vertical stress of 40 MPa and a mud pressure of 20 MPa. Although these conditions do not allow us to exploit the full benefits of the stress relief effect, they do show that the contribution of peripheral groove on performance. The stress relief effect, widely influenced by the depth drilled, will only improve the results obtained. After fully engaging the bit in the rock (cutting structure plus passive guard), the high-pressure water jet was activated for about 10 cm of drilling and then stopped without changing the operating parameters. We applied a WOB of 2 tons and a rotation speed of 40 RPM.

4.2 Results and discussion

The goal of the experiments was to quantify the impact of slotting peripheral groove on the ROP, compared to conventional percussive drilling. Figure 13 shows the raw drilling parameters (WOB, ROP and pressures) during drilling with or without high pressure water jet slotting. Firstly, it can be noted that the hammer was used at half power with a pressure drop of 6 MPa whereas full power is obtained with a pressure drop of 10 MPa across the hammer. It can be observed that the penetration rate is about 0.8 m/h for 5 tons WOB when the high pressure water jet was stopped after 1125 seconds. On the other hand, between 1010 and 1125 seconds, an average ROP of 2.2 m/h is observed for the same level of WOB around 5 tons. That leads to an 270 % improved ROP. It can also be noted that the increase in mud pressure from 20 to 30 MPa at 1060 seconds did not change the penetration speed of the bit.

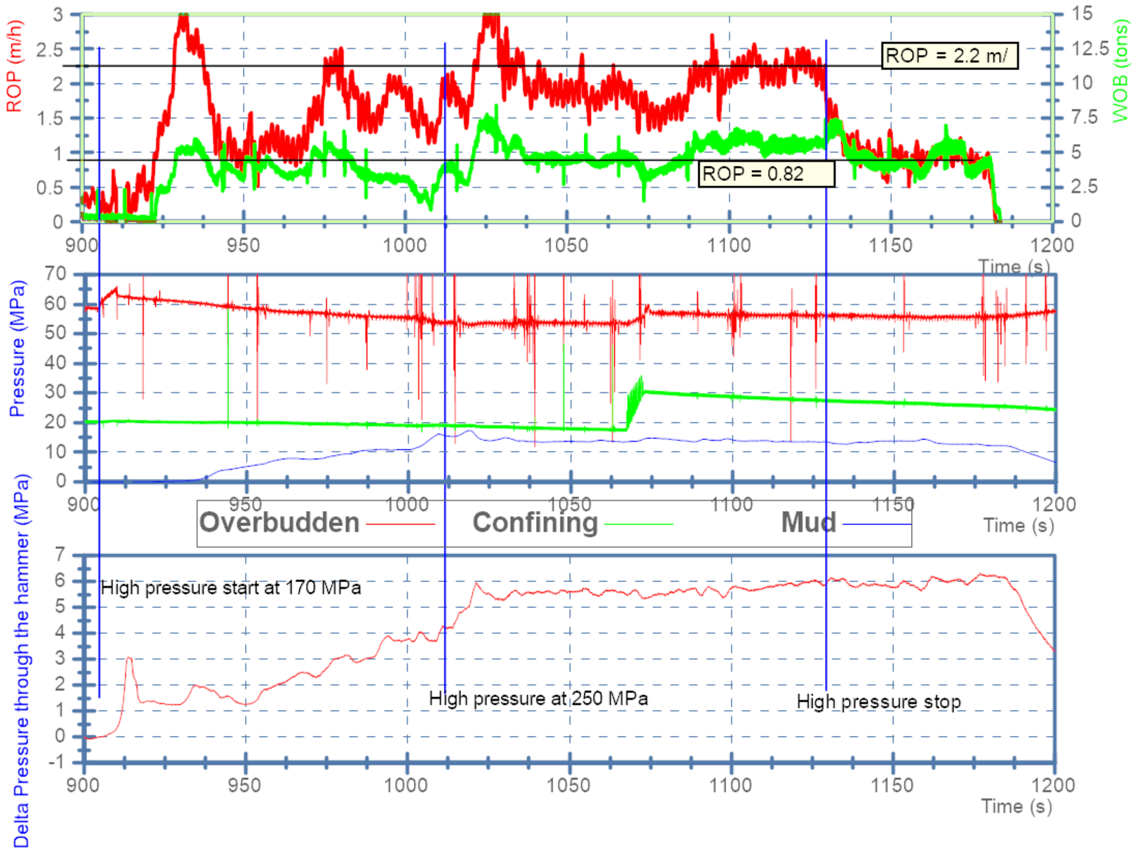

Figure 13: raw data of the combined HPWJ and percussion drilling

The drillability of the bit is defined as the ratio of the penetration speed to the rotational speed and times the WOB. It allows the variations of the two operating parameters WOB and RPM to be ignored. It is expressed as:

$$Drillability = \frac{WOB}{ROP * RPM} \; in \;\; mm/ton/rev$$

Figure 14 shows the evolution of drillability over the same period. The previous results can be seen with a strong increase in drillability when the peripheral line is dug with the high pressure water jet.

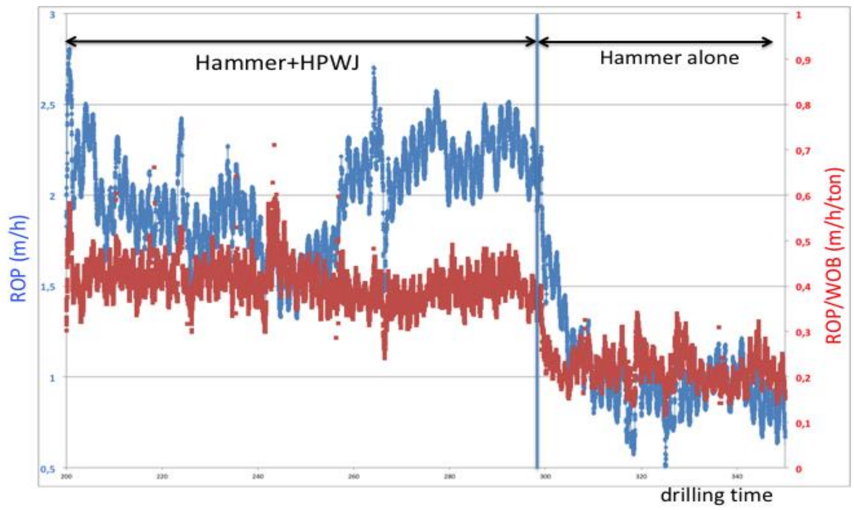

Figure 14: Drillability with and without the high pressure water jet slotting

4. CONCLUSION

The European ORCHYD project seeks to improve penetration speed for deep geothermal drilling. The objective is to increase the ROP in hard rock such as granite by a ratio of at least 4 from 1 to 2 m/h to 4 to 10 m/h. The technique implemented in this project consists of coupling two mature technologies: high-pressure water jet cutting and percussive drilling. Basic scale testing of a single high pressure water jet in a representative deep borehole environment showed that it was possible to reach groove depths of one centimeter if the injection pressure was high enough. The first tests conducted on the scale of a full-size drill bit under representative conditions showed that an ROP improvement of 2.5 ratio was possible before any optimisation of the new drilling technology. The goal of a fourfold increase in low speeds is therefore highly achievable. Indeed, for deep drilling, the stresses at the bit rock interface will be higher and therefore the stress relief effect more pronounced as the peripheral groove is cut. This, coupled with optimising the placement of the inserts according to the stress level and the peripheral slot, should enable the objective of a 4-fold increase.

Acknowledgements

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