Improvement of drilling performances in deep geothermal drilling in hard rocks, by using a novel Hydro-Mechanical Drilling

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ABSTRACT

A new drilling technique developed in the framework of the European H2020 *ORCHYD* project combines two mature technologies, high pressure water jetting (HPWJ) and hydraulic hammer, into a fully fluid driven system adapted to deep geothermal drilling in hard rock. This hybrid development requires the optimization of several processes including the release of high stress concentrations at the bottom of the hole during deep drilling, by playing on the geometric configuration of the bottom-hole. The preliminary results of this project, presented in this paper, concerns the study of the best geometrical configurations: bottom-hole profile (bit profile) and peripheral groove to release stresses in the immediate vicinity of the drilling bit action, in the context of hard rocks such as granites. It has been shown that the combination of a concave bit profile with a peripheral groove of a desired depth can significantly release stress concentrations in the rock undergoing the drilling action, thereby reducing its resistance to the drilling action and even generating tensile stresses highly beneficial to the drilling process. Initial laboratory tests with a flat hammer bit combined with a 208 MPa peripheral HPWJ, under moderate hydrostatic pressure, have shown promising performance in 150 MPa UCS granite. It is expected that under higher stress and pressure regimes, synonymous with deeper drilling, and for a slightly concave profile hammer, the creation of the peripheral groove of a desired depth should further reduce stresses in the immediate vicinity of the bit action, thereby reducing the resistance of the rock to the drilling action and improving the drilling performances.

1. INTRODUCTION

Geothermal energy harnesses the heat of underground rocks to convert water to steam and supply an uninterrupted power as opposed to wind and solar energy sources. This makes geothermal energy a leading candidate for a carbon neutral, efficient and reliable source of renewable energy supply across the globe. However, the current drilling methods to reach the rocks at a depth of more than 4 Km are slow and inefficient - making geothermal sources supply less than 2% of the global energy mix.

One of the factors affecting the cost of deep geothermal drilling is the difficulty of drilling deep hard formations with an acceptable rate of penetration (ROP) using conventional rotary drilling bits such as roller cone and PC bits. Drilling bits have undergone remarkable evolution over the last two decades, mainly by designing advanced cutters (material, shape and set-up) as well as bit geometry and profile. Advanced rotary drilling bits have been developed providing improved drilling performances in hard and abrasive formations. However, it is unrealistic to expect spectacular improvements from the current mechanical drilling techniques, because conventional rock destruction processes cannot accommodate the very high hardness of deep rocks, crystalline ones in particular.

One of the solutions to accommodate these constraints related to rock hardness and abrasiveness, is to sufficiently weaken the rock at the bottom-hole, before it is attacked by a conventional drilling bit. Hydro-mechanical drilling is a mature solution to achieve this objective, provided that the processes involved are optimized. Such solution is developed within the *ORCHYD* European project (Novel Drilling Technology Combining Hydro-Jet and Percussion For ROP Improvement In Deep Geothermal Drilling) of the Horizon 2020 program, and presented in this paper.

2. TECHNOLOGICAL APPROACH

The starting point of the *ORCHYD* project is that deep rocks are subject to high down-hole stresses, which make the rock more resistant, reducing the efficiency of the mechanical action of the drilling bit . To address this problem, several questions are raised:

- How does stress concentrate at the bottom-hole in the immediate vicinity of the drilling bit?
- Can these stresses be reduced and how can this be achieved?
- How effective it is to modify the bottom-hole profile?
- How effective it is to create new free surface, by slotting groove at the drilling face?

The *ORCHYD* project aims to develop a non-conventional, fully fluid driven drilling system. To achieve this technological development, several processes should be optimised on:

- How to maximize the process of stress release?
- How to slot effectively, while drilling, circumferential single or multiple grooves at desired depth using High pressure water jet up to 250 MPa?
- How to produce in-hole High Pressure using a down-hole pressure intensifier?
- And finally, how to adapt the down-hole percussive rotating bit hammer, to take full advantage from the modified bottom-hole stress regime and profile, including the slotted grooves.

This paper presents the preliminary numerical and experimental results of this development including the first results of a laboratory full scale pilot tests carried out in order to validate the concept of this new drilling system.

3. NUMERICAL ASSESSMENT OF STRESS CONCENTRATION ON THE BOTTOM-HOLE

The literature review shows a large number of studies on cutting and coring process in deep rocks. In this framework, the main purpose of stress analyses is often to explain some phenomena such as borehole instability and failure or core disking Bahrani et al. (2015). As far as we know, the state of stress regimes in highly stressed deep rocks as well as the process of stress release has not been studied when applied to the drilling mechanism in order to improve ROP.

Numerical simulations have been performed using the Abacus Software under axisymmetric conditions. The target depth of the project is located between 4 and 6 km, where the geological formations are mainly constituted of hard crystalline rocks, granites in particular.

Table 1 shows the characteristics of the studied Sidobre granite. These parameters were obtained on undisturbed laboratory macroscopic scale samples. Based on the mechanical parameters on table 1 deduced from classical compressive tri-axial tests, the stress state not lead to an exceeding of the failure criterion of the studied granite, which justified the use of an elastic simulation in a first step. Naturally, when loading due to the action of the drilling bit is considered, a model taking into account the failure process will be used.

Table 1: Characteristics of the studied granite

Density	2635 kg/m^3
Sound velocity	5600 m/sec
Young modulus	60 GPa
Poisson ratio	0.25
Uni-axial Tensile Strength (UTS)	8 MPa
Uni-axial Compressive Strength (UCS)	150 MPa
Cohesion	25 MPa
Friction angle	55 deg

The results presented below correspond to the case of 4 km drilling depth, described by an initial horizontal and vertical stress state Sh=Sv=-100 MPa and a -40 MPa applied drilling mud pressure. The drilled hole diameter is 20 cm and the groove width is 5 mm. Three bottom-hole profiles are considered: convex and concave bit of ±2.5 cm curvature radius and a flat profile.

Figure 1 shows the radial stress concentration at the bottom-hole depending on its profile. The zero index stands for the rock initial state before drilling the hole. The stress concentration appears when the stress ratio is greater than 1. The convex profile results in a higher stress concentration rather at the centre of the bottom-hole whereas for the concave and flat profiles, this occurs more at the periphery of the bottom-hole. Interestingly, the concave profile exhibits stress relaxation except at the periphery of the hole.

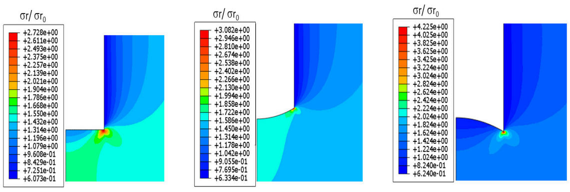

Figure 1: Radial stress concentration factor for flat, convex, and concave profiles

In order to quantify the stress concentration around the bottom-hole, the normalized mean stress (P/P0) is considered, representing the variation of the mean stress at a given point on the bottom-hole. In addition, in order to assess the groove depth effect on the stress state at the bottom-hole, the dimensionless factor η=H/D is introduced, where H is the groove depth and D the bottom-hole radius. Figure 2 illustrates the variation of the mean stress at point M, centre of the hole, when the ratio η increases, for 3 down-hole profiles representative of the action of three different drilling bit profiles. It can be noted that the average stress continues to decrease when the groove is deeper and this phenomenon is more accentuated in the case of the concave profile. This shows that, for a given drilling diameter, it is possible to play on the depth of the groove to maximize the de-confinement of the rock near the drilling action.

This example shows a 60% reduction of the mean stress when the groove depth is 20% of the hole diameter, while, with convex profile, this reduction requires a groove depth of 50% of the hole diameter. This means that if we consider a hole diameter of 20 cm, with a concave profile, it is necessary to slot a 4 cm peripheral groove, while with a convex profile, a groove depth of 10 cm would be necessary, which is almost impossible to achieve with a high pressure water jet in a granite as hard as the one studied, under deep hole pressure conditions. This shows the interest of combining a slightly concave profile with a peripheral groove of a certain depth.

These numerical results are also illustrated in the diagram of invariants, the stress deviator as a function of the mean stress (Figure 3a). On the same graph, the Hook&Brown failure criterion, adjusted on the characteristics of the studied hard granite, is also plotted. We can see that the stress path remains below the failure criterion and that when the bottom of the hole includes a peripheral groove, the mean stress and the deviator are much smaller than when there is no groove. Note that it is also possible to generate situations where tensile stresses can appear in a zone close to the drilling action, which is quite favourable to the drilling process. This is particularly the case when an initial anisotropic stress state and a concave profile are combined, as can be seen in figure 3b. This is in line with the results of Li et al. (2013) and Wu et al. (2018) of their analysis of the observed disking process of rock cores extracted from deep boreholes.

Note finally that in these simulations, no action of the drilling bit is considered, the purpose here is to show that stresses can be released in the immediate vicinity of the cutting process to weaken the rock and thus reduce its resistance that it would oppose the drilling action.

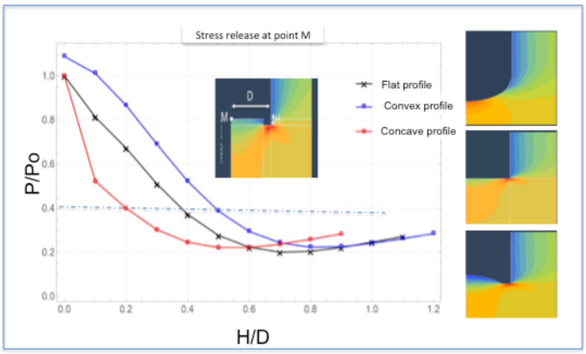

Figure 2: Mean stress concentration factor for flat, convex, and concave profiles, according to the peripheral groove depth.

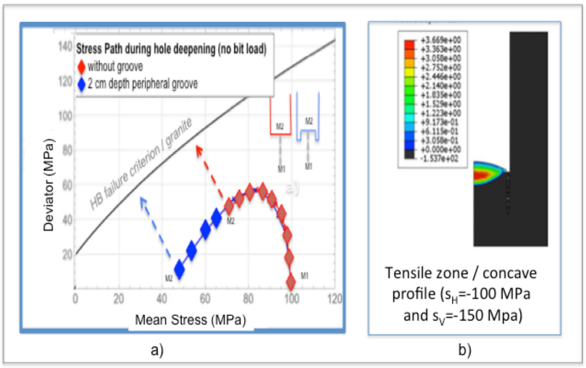

Figure 3: a) Stress path in the diagram Deviator-mean stress at point M, centre of bottom-hole surface, with and without groove of 2 cm depth, b) major principle stress under anisotropic stress state.

4. FULL-SCALE EXPERIMENTAL DRILLING INVESTIGATION

MINES Paris/Armines has developed a large panel of experimental devices and procedures for laboratory test to realize a complete characterization of downhole drilling system. The drilling rig used in this study allows to test drilling bits (rotary and percussive) at full diameter (up to 12 ¼") under realistic down-hole pressures (up to 5000 m depth), temperatures (up to 350°C) and drilling parameters (20 tons WOB, 1000 RPM, all types of drilling mud). Fully instrumented to monitor the drilling process (ROP, directional behaviour, wear, vibration, lifetime of the equipment, etc…), this setup can accommodate realistic downhole conditions by creating hydrostatic, confining and pore pressure using independent pressure lines. The test bench has turnkey solutions to test directional drilling and to simulate the steerable systems (figure 4).

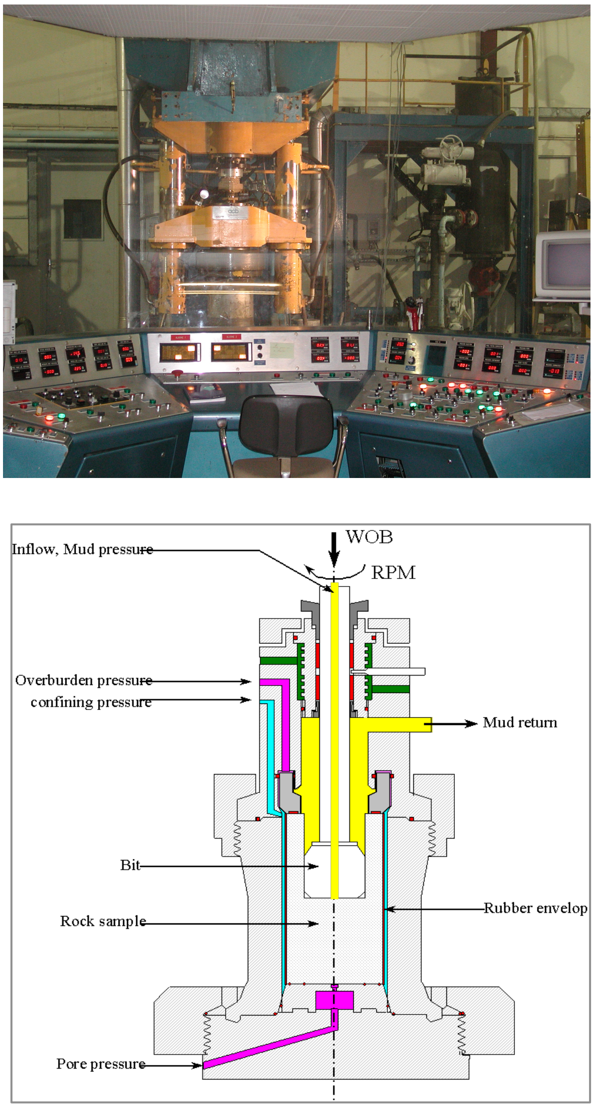

Figure 4: The drilling bench of MINES Paris/Armines.

In order to test the hammer equipped with high pressure water jet system, modifications were made to the original configuration of the drilling rig. This was done to accommodate the high pressure system from the top swivel to the bit (figure 5). The high pressure was provided by a WOMA type 250 M P18 pump, with a maximum flow rate of 30 L/min at 250 MPa and nozzle diameter of 1 mm.

The drilling bit used is a 6’’ hammer manufactured by DrillStar Industries, partner of the *ORCHYD* project, modified 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 and thus increase the ROP. The stand-off distance for the extended nozzle was set constant at the closest possible value, around 6-7 mm, for all experiments.

The bit rotation speed was set constant at 30 RPM and the weight on bit varied between 60 kN and 140 kN. Only tap water was used as drilling fluid.

The tested rock type was Sidobre granite. The dimensions of the samples fit the requirements by the test bench with a diameter of 310 mm and a height of 380 mm. The mechanical and physical rock properties were given in table 1. This granite is considered as impermeable (permeability less than 0.05 mD).

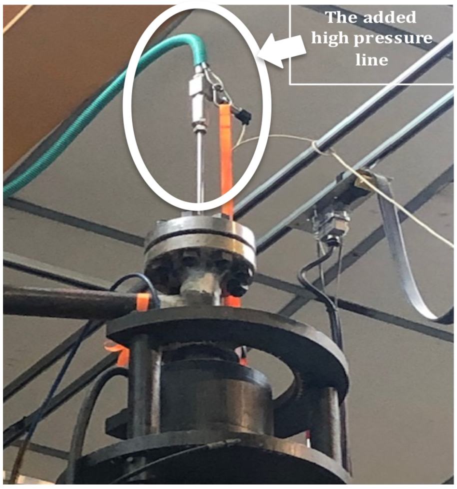

Figure 5: Modified upper part of the drilling simulator, incorporating a high pressure mud jet delivery and management system.

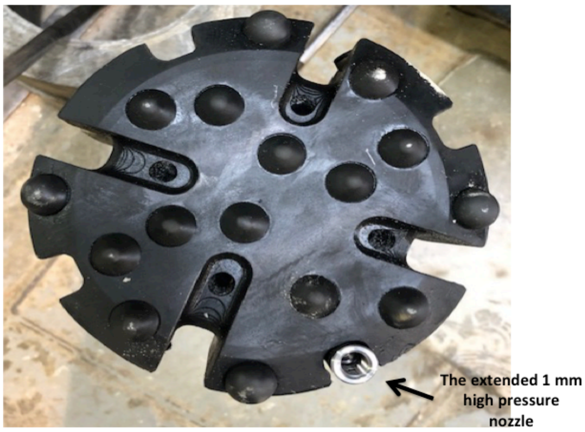

Figure 6: The modified 6’’ hydraulic hammer bit

5. RESULTS

The goal of the experiments was to quantify the impact of slotting peripheral groove on the ROP, compared to conventional percussive drilling. Only tests under hydrostatic pressure of 25 MPa on the rock sample have been carried out till now. No effect of the drilling bit profile, described above, could yet be studied experimentally before the writing of this paper. Nor could the effect of high geostatic stresses and the effect of their relieving on the increase of ROP since the stresses regime tested was low to moderate. Figure 7 shows the first results of drilling simulator tests with tap water as drilling and jetting fluid. These preliminary results, using a 208 MPa water jet, show that the designed drilling system allows to increase by a factor up to 80% the ROP in the hard sidobre granite. This result should be understood as the contribution of the peripheral groove, as a free surface, favouring the reflection of compression waves induced by the dynamic action of the hammer. This could generate tensile stresses that facilitate the drilling process. We believe that substantial improvements in terms of ROP gain should be obtained under much higher stress regimes than those tested in this first phase of laboratory tests. This would allow the peripheral groove to play its role as a stress concentration release system under high stress.

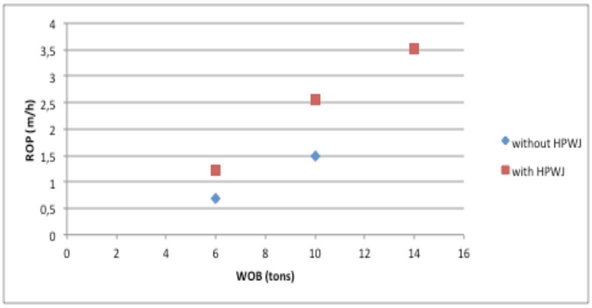

Figure 7: Drilling performances of hydraulic hammer with and without peripheral 208 MPa water jet, in Sidobre granite.

6. CONCLUSION

This new technology, based on the combination of a hydraulic hammer and a high-pressure jet to slot a peripheral groove, shows promising performance in hard granite. It is expected that under higher stress regimes, synonymous of deep drilling conditions, the creation of the peripheral groove should allow the stresses in the immediate vicinity of the drilling bit action to be relieved, reducing the resistance of the rock to the drilling action. This effect should be cumulative with the observed effect of the groove as a free surface for the reflection of the compressive waves induced by the dynamic action of the mud-hammer. A large testing programme is currently being prepared and carried out at the MINES Paris/Armines drilling laboratory.

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