



HAL
open science

Enhancing drilling performance of mud hammers by combining high pressure water jets slotting

Laurent Gerbaud, Emad Jahangir, Naveen Velmurugan, Hedi Sellami, F Cazenave

► **To cite this version:**

Laurent Gerbaud, Emad Jahangir, Naveen Velmurugan, Hedi Sellami, F Cazenave. Enhancing drilling performance of mud hammers by combining high pressure water jets slotting. 57th US Rock Mechanics/Geomechanics Symposium, ARMA, Jun 2023, Atlanta (USA), France. hal-04436760

HAL Id: hal-04436760

<https://hal.science/hal-04436760v1>

Submitted on 3 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Enhancing drilling performance of mud hammers by combining high pressure water jets slotting

Gerbaud, L.

Mines Paris-PSL University, Geosciences Department, Fontainebleau, France

Jahangir E., Velmurugan, N. and Sellami, H.

Mines Paris-PSL University, Geosciences Department, Fontainebleau, France

Cazenave, F.

Drillstar Industries, Pau, France

Copyright 2023 ARMA, American Rock Mechanics Association

This paper was prepared for presentation at the 57th US Rock Mechanics/Geomechanics Symposium held in Atlanta, Georgia, USA, 25-28 June 2023. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its

ABSTRACT: Geothermal energy is a leading candidate in fulfilling our transition efforts to a clean, sustainable, non-intermittent and renewable energy source. However, high drilling costs act as a showstopper in geothermal exploration. One of the main factors contributing to this high price is the drop in drilling performance when drilling through hard crystalline granite rocks that are usually found at depths greater than 4 km. Studies show that increasing the drilling performance by a factor of 4 with respect to the current drilling rates of 1-2 m/h can reduce the drilling costs up to 65%.

Percussion drilling using down the hole (DTH) hammer has proven to be efficient in drilling through hard rocks. In ORCHYD project, we combine high-pressure water jet (HPWJ) with a DTH hammer to increase the rate of penetration (ROP) by a factor of 3 to 4. The HPWJ creates a peripheral groove in the rock surface facing the drill bit. This peripheral groove of few millimeters is expected to release the rock surface from the surrounding confining stress regimes – requiring lower energy to break the rock using percussion drilling. It is also expected that the free surface created by the groove aids in reflecting the waves created during percussion. A DTH mud hammer is modified to allow the flow of HPWJ through the hammer body and redirect it to the periphery of the drill bit. The prototype developed in this work was tested on a laboratory scale drilling test rig under realistic downhole drilling conditions. At the current stage of the project, it is demonstrated that slotting peripheral grooves using the HPWJ improves the ROP of the hammer drilling system by a factor of 2 to 2.5.

1. INTRODUCTION

Deep geothermal energy is a promising and increasingly important source of energy production worldwide. Geothermal electricity production is particularly attractive for both rich and poor economies due to its ability to generate both heat and electricity, which are in high demand. Enhanced Geothermal Systems (EGS) are becoming more popular as they allow for combined electricity and heat production at geothermal power plants (Angelone (2014)). However, drilling operations are a major component of the total project cost, representing up to 40% of the total cost (Angelone (2014)). For a 3 km well, the cost can reach up to 15 M€ (Angelone (2014)), which makes it challenging to extract geothermal energy in an economically viable manner.

One of the main challenges in deep geothermal drilling is the speed of penetration. Hard formations, such as granite, can be difficult to penetrate using conventional

drilling bits, such as roller cone and PDC bits, resulting in low rates of penetration (ROP) (Cardoe et al. (2021); Baujard et al. (2017)). A number of factors affect the drilling process, including chip hold down, balling-up of the hole bottom and drill bit, pore pressure and mud filtration, overburden pressure, mud pressure, formation pressure, bit size and hydraulics, among others (Angelone (2014)).

Granite and basement formations are known to remain brittle even under deep drilling conditions (Hokka et al., 2016). This makes percussive drilling a suitable method for increasing the drilling speed in such formations, especially where hard and abrasive rocks are present and subjected to high geostatic and hydrostatic pressures. However, these conditions can increase the rock's resistance and complicate the drilling process, resulting in a substantial drop in the rate of penetration (Gnirk and Cheatham, 1965; Han et al., 2006).

To overcome these challenges, drilling techniques must be adapted and optimized for these extreme conditions. Down-the-hole (DTH) percussive drilling is a technology that involves applying a series of impacts via an oscillatory movement of a piston, which impacts a drill bit at a frequency of 20–30 Hz with a velocity of 1–10 m/s. This leads to rock fragmentation by compressive and tensile forces under the drill bit, which is enabled by the drill bit buttons, also called inserts that are in contact with the rock surface. At each impact, compressive waves travel through the drill bit down to the rock material, enabling the bit's penetration by indentation of the inserts into the rock (Hartman, 1959). Recent developments in DTH and percussive drill bit design have led to 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. The potential of JARD to significantly enhance the ROP in deep drilling operations and improve the efficiency and cost-effectiveness of the drilling process has been demonstrated in previous studies (Guan et al., 2014; Lu et al., 2012, Liao 1994, Xue 2012). 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. Kolle et al. (1991) and Veenhuizen et al. (1997) demonstrated the potential of high-pressure jet-assisted roller cone bits in comprehensive laboratory and field testing research studies. Stoxreiter (2019) performed experiments on high-pressure jet-assisted rotary drilling with a roller cone in hard-to-drill granite, which led to an increase in ROP by a factor of more than 1.7 compared to performance without JARD.

The present study aims to demonstrate how high-pressure jet-assisted drilling can improve performance by combining it with percussive drilling in crystalline rock. The study was performed using a commercial percussive drilling system to which a high-pressure water jet line was added on the bit periphery. This paper analyses the effect of a peripheral groove on the downhole stress distribution and explains the concept of “Stress release”. It also focuses on the effect of a pre-existing groove on the percussive action of one insert and summarizes the experimental setup to validate the combined effect of percussive drilling and high-pressure water jet slotting.

2. PERIPHERAL GROOVE EFFECT

2.1. Stress release effect

It is well-known that the confining stresses on rock surfaces increase with depth due to the weight of the overlying rock, and that rock resistance to cutting increases with confining stresses (Jaeger and Cook (1979); Ma et al (2011)). Creating a borehole alters the stresses around the rock layer and influences the energy required to break the rock – more energy is required as the wellbore extends deeper (Bai and Zhou, 2010).

The ORCHYD (Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in Deep Geothermal Drilling) project aims to exploit the principle that creating a peripheral groove on the rock surface can release it from confining stresses, emulating a near-surface condition. The effect is further influenced by the profile of the bottom hole induced by the bit profile and the cutter layout (Gerbaud et al (2022)).

Figure 1 demonstrates the radial stress concentration factor defined as the ratio between the current radial stress and the original one with different bit profiles. It can be seen that the stress at the bit-rock interface is significantly lower for the concave shape compared to the convex shape. It can be seen that the flat bit generates an intermediate stress. The stress level at the bit-rock interface can be significantly reduced by adapting the bit profile.

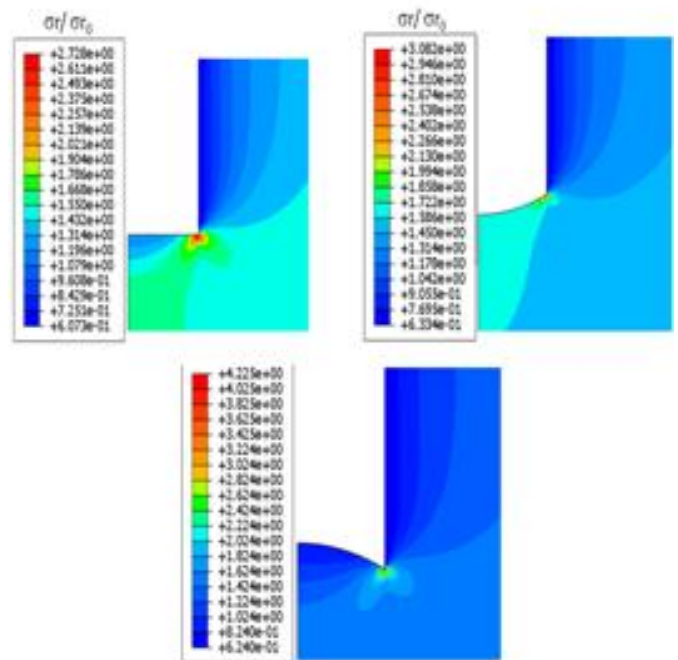


Figure 1: Radial stress concentration factor for flat, convex, and concave profiles

The stress release effect is enhanced with a deep peripheral groove. Figure 2 shows that the maximum stress release is obtained at a ratio of 0.4 (more than 5 cm) for a concave bit profile.

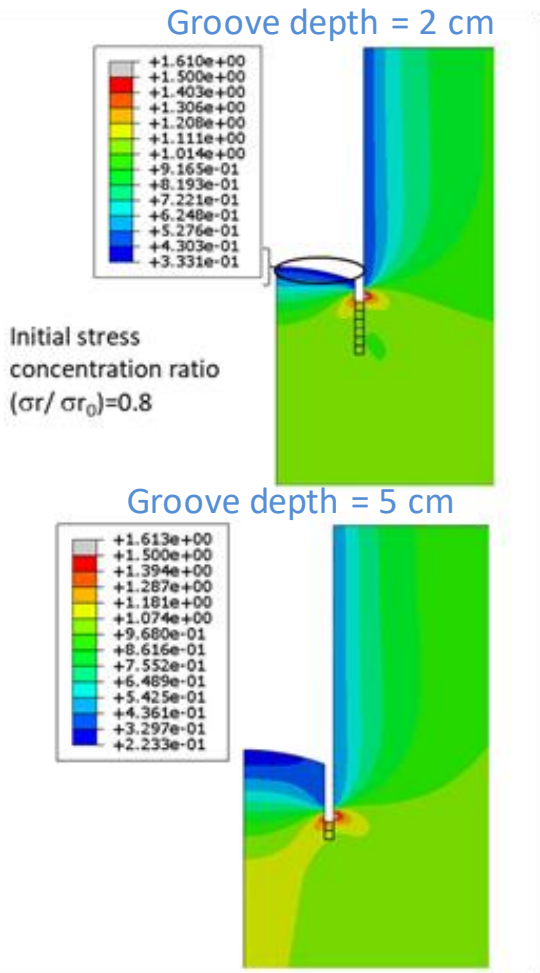


Figure 2: Effect of peripheral groove on the stress release

2.2. Insert-HPWJ slot interaction

The presence of the peripheral groove (HPWJ slot) changes the stress state of the rock in interaction with the insert. The insert comes into contact with the rock which has a released stress and consequently could be broken more easily. The interaction is dependent to the insert distance with the slot and the hammer contact velocity. To show this phenomenon, an axisymmetric FEM dynamic analysis will be presented in this section. The insert location will be fixed, and the groove depth (0.1-3 cm) and the contact velocity will vary (3-9 m/s). The following figure shows the studied configuration where the failed zone will be considered as the cut rock zone and its volume will be calculated.

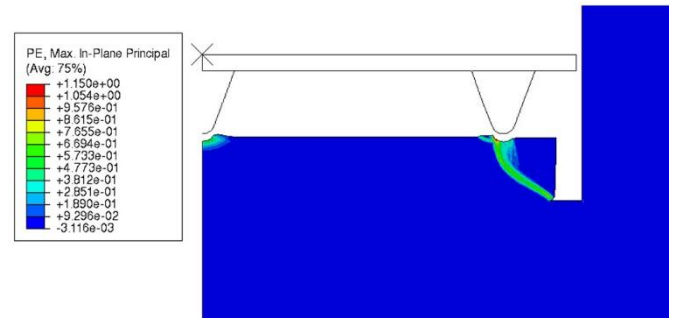


Figure 3: Insert rock interaction with the peripheral groove.

The following figure shows the obtained results for different groove depth and different velocities. A dimensionless parameter, h/R (groove depth: h , Bottomhole radius: R), has been introduced to summarize the mentioned effects.

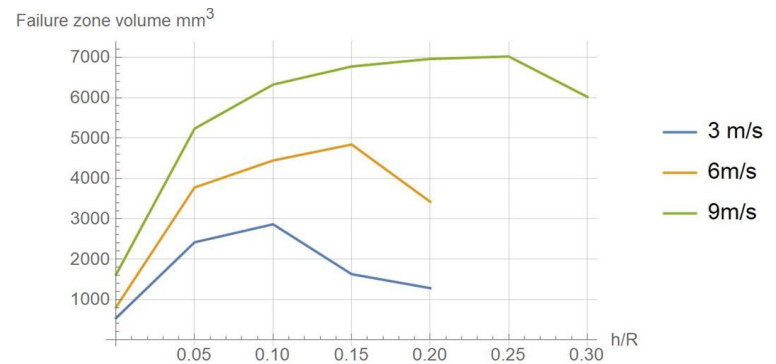


Figure 4: Failure zone volume according to the groove depth and contact velocity.

This results show the importance of the optimal groove depth and the appropriate contact velocity to get a higher rock cut volume. In fact, each contact velocity presents an optimum value for a given groove depth. It seems that when the groove gets too deep (3cm) the interaction between the insert and groove's bottom decreases. In the perspective of this simulation task, it is convenient to make the same analysis with the complete tool geometry to optimize its design whit respect to the insert's location.

3. EXPERIMENTAL METHODOLOGY

3.1. Experimental Set Up

The Mines Paris drilling bench (Figure 5) is an experimental setup that enables the testing of full-scale drill bits under deep drilling conditions, while controlling the key variables of the drilling process. The rock sample is enclosed in a pressure cell (Figure 6), where it is subjected to constant but independent overburden pressure, confining pressure, and pore pressure. The drill bit can apply a Weight On Bit (WOB) of up to 245 kN, which is achieved through two lateral pistons, while the rotation of the drill bit (up to 1000 RPM) is generated by a DC electric motor installed on

the drilling floor of the bench. This motor is connected to the drill shaft via a gearbox. The drilling mud of any type, such as water, WBM or Oil Based Mud, is injected at the drill bit through the drill pipe by using a Gardner-Denver PL7 pump. The tests can be performed with either WOB or ROP control.

Throughout the drilling tests, the different pressures, temperature, bit torque, and ROP are continuously monitored and recorded. The data are sampled at a rate of 200 Hz and saved in ASCII file format.



Figure 5: Drilling test rig

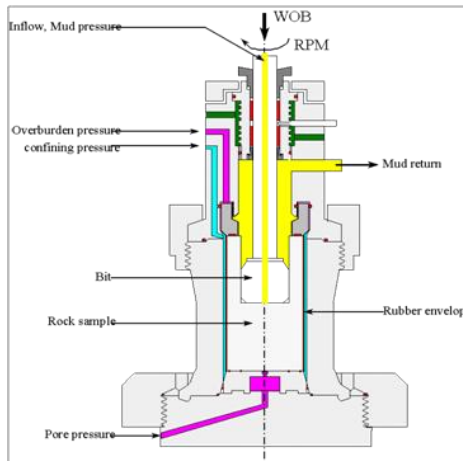


Figure 6: Schematic of the bit-rock interaction in the drilling cell

The experimental set-up was modified to carry out the tests for the new drilling technique:

- The final shaft that enters the cell and on which the bit is usually screwed was replaced by the mud motor. The rotating seal had to be adapted because the hammer diameter was larger than the shaft diameter.
- To connect the HP pump to the HP nozzle fixed on the drill bit, a high-pressure (HP) line was

installed on the drilling bench. This transmission line features a swivel connection system at the top of the drill shaft, which includes various complex sealing systems. These ensure a steady supply of the HP jet while also allowing for free rotation of the system, thanks to the presence of tubes, tees, bends, swivels, sensors, and other components. The WOMA pump type 250 M P18 provides the high pressure, with a maximum flow rate of 30 L/min at 250. At the maximum pump operating pressure, the pressure loss along the HP line is approximately 10 MPa.

3.2. Experimental plan

Tests were performed with 6" bits (Figure 7). In order to compare drilling performances, two types of drilling technology were tested with and without JARD:

- Percussive drilling: The bit 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.
- Rotary drilling with a roller cone: The bit is an IADC 713 adapted for hard rock drilling. A high-pressure system with a pressure of up to 220 MPa has been added on the bit periphery via a special sub designed to exit the high pressure from the center of the line to the bit periphery.



Figure 7: percussive (left) and roller cone bit (right) with the HPWJ line

Sidobre granite was used as the reference rock drilled in these tests (Table 1)

Tableau 1: Mechanical characteristics of Sidobre Granite

Name of Rock	UCS (MPa)	UTS (MPa)	Grain size min-max (mm)
Sidobre	221	8	2 – 10 mm

Due to the limitations of the test rig, we were only able to simulate a depth of 2000 m, resulting in a horizontal and vertical stress of 40 MPa and a mud pressure of 20 MPa. Although these conditions did not allow us to fully utilize the stress relief effect, they did reveal the impact of the peripheral groove on performance. As the stress relief effect is greatly influenced by the depth of drilling, better results can be achieved with increased depth. After the cutting structure and passive gage of the bit were fully engaged in the rock, we activated the high-pressure water jet for approximately 10 cm of drilling before stopping it without altering any of the operating parameters. Our testing involved a weight on bit (WOB) of 2 tons and a rotation speed of 40 RPM

4. RESULTS DISCUSSION

4.1. Energy efficiency

The objective of the experiments was to quantify the impact of slotting the peripheral groove on the ROP, and to compare percussion drilling methods to traditional roller cone drilling. The tests were carried out in Sidobre granite (Table 1) with a confining and slurry pressure equal to 20 MP and a compaction pressure equal to 40 MPa. Figure 8 shows the experimental data for the roller cone test. Three distinct phases can be seen. The first phase is the engagement of the bit with the rock sample. The penetration rate decreases at constant weight and reaches 1.2 m/h once the bit is fully engaged. The second phase of the test is carried out without the addition of the high-pressure water jet with a constant weight of 60 kN and a constant ROP of 1.2 m/h. The third phase of the test corresponds to the addition of the high pressure water jet at the periphery. No improvement in ROP was observed except when the WOB was increased to 85 kN. The addition of high pressure did not improve the ROP, which is confirmed by the absence of groove at the rock face after drilling. This absence of groove is explained by the difficulty of placing a high-pressure nozzle very close to the drilling face due to the parabolic profile at the periphery linked to the shape of the cone (the efficiency of the jet is reduced when the distance between the jet outlet and the target increases).

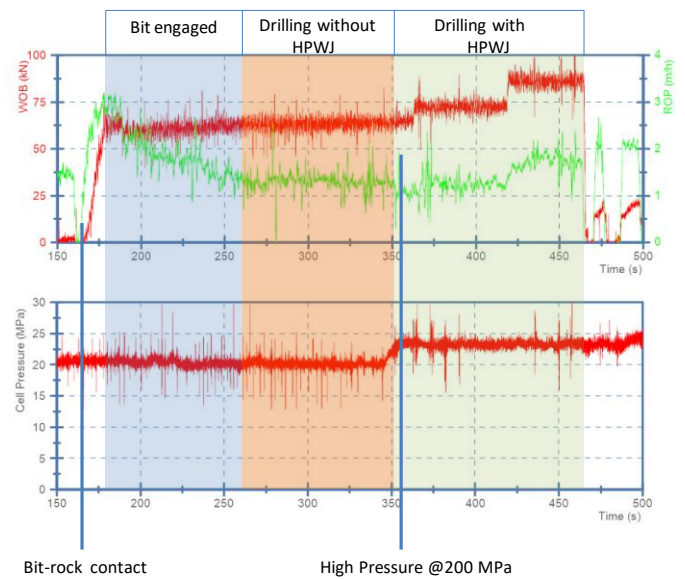


Figure 8: raw data of the combined HPWJ and roller cone drilling

Figure 9 shows the experimental data for the hammer test. Again, three distinct phases can be seen. The first phase corresponds to the engagement of the bit and the increase in pressure and efficiency of the hammer. The second phase corresponds to drilling with percussion and the high-pressure water jet. A penetration speed of around 2-2.2 m/h is observed for a WOB between 40 and 55 kN. At t=1130 seconds, we stopped the high-pressure water jet and a decrease in ROP to 0.9 m/h was observed throughout the third phase. Figure 10 shows a picture of the working face where the peripheral groove can be seen. Indeed, due to the flat profile of the bit for percussion, it was easy to place the high-pressure nozzle as close as possible to the cutting face (Figure 7). The beneficial effect of the peripheral slotting can be seen very clearly, as it increases the penetration speed by more than 2 times with percussive drilling.

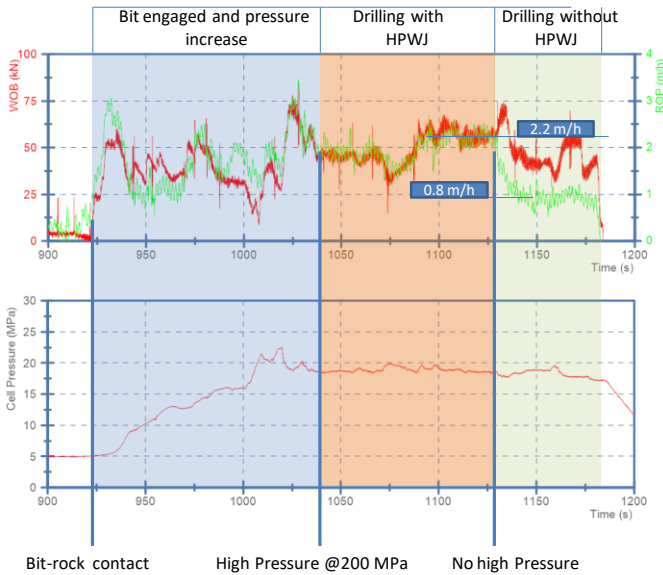


Figure 9: raw data of the combined HPWJ and percussion drilling

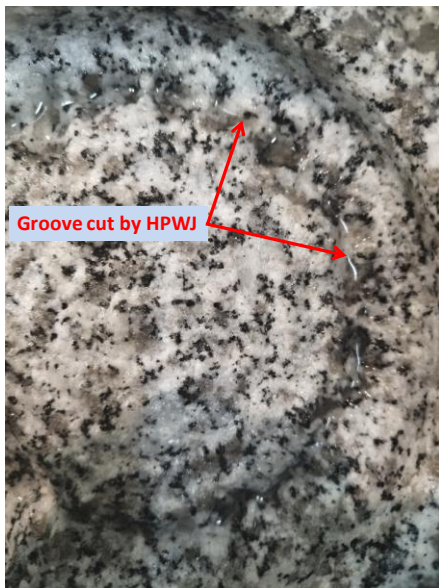


Figure 10: View of the bottom hole after drilling with High Pressure Water Jet

Drillability is an index defined as the ratio of the Depth Of Cut (DOC) per revolution to the weight on bit and allows different tests to be compared with each other, disregarding variations in WOB (Eq. (1)). Higher is the drillability, better is the drilling performance.

$$\text{Drillability} = \frac{DOC}{WOB}$$

with DOC, depth of cut, in mm/rev and WOB in kN.

Figure 11 shows a synthesis of the tests carried out with roller cone and percussion coupled or not with the high pressure water jet by giving the drillability for each drilling technique. As already observed by Souchal et al (2017), the drillability of the hammer is twice as high

(0.1 versus 0.045) as that of the roller cone. We also note that the creation of a peripheral groove with the high-pressure water jet multiplies the drillability of the hammer by almost 2. There is therefore a ratio of 4 between the initial drillability of rotary drilling with a roller cone and the new technique developed in the ORCHYD project, which combines percussion drilling with high-pressure water jet cutting.

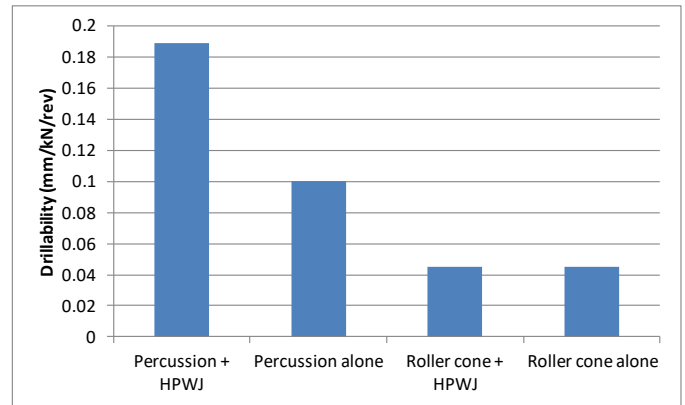


Figure 11: Drillability for each drilling techniques

5. CONCLUSIONS

The European ORCHYD project aims to enhance the rate of penetration of deep geothermal drilling by implementing a technique that combines high-pressure water jet cutting and percussive drilling. The project seeks to increase the ROP in hard rock, such as granite, from 1-2 m/h to 4-10 m/h, which is at least a fourfold improvement. The full-size drill bit testing under representative conditions revealed a 2 times ROP improvement for the percussive drilling and a 4 times ROP improvement when it is compared with the standard technique such as rotary drilling with a roller cone. The objective of a fourfold increase in ROP at low speeds is already reached and should be validated in deep drilling, where the stress relief effect will be more pronounced with the cutting of the peripheral groove. By optimizing the placement of the inserts according to the stress level and peripheral slot, the target of greater improvement can be achieved.

Acknowledgements

We would like to thank the team of the Pau drilling laboratory, in particular Cedric Chambres and Eric Phelipot for their contribution to this testing program. This project was funded by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 101006752.

REFERENCES

1. Angelone M., and Labini S. S. (2014). Energy Research Knowledge Centre – *European Commission*,
2. Bai, Q. and Zhou, X. (2010). *Drilling Engineering*. Petroleum Industry Press
3. Baujard, C., Hehn, R., Genter, A., Teza, D., Baumgärtner, J., Guinot, F., ... & Steinlechner, S. (2017). Rate of penetration of geothermal wells: a key challenge in hard rocks. *In Workshop on geothermal reservoir engineering*. Stanford University, USA,
4. Cardoe, J., Nygaard, G., Lane, C., Saarno, T., & Bird, M. (2021). Oil and Gas Drill Bit Technology and Drilling Application Engineering Saves 77 Drilling Days on the World's Deepest Engineered Geothermal Systems EGS Wells., *In SPE/IADC International Drilling Conference and Exhibition*. OnePetro
5. Gerbaud, L., Pubill, A., Adannawy, H., Rouabhi, A., Lamazouade, M., Souchal, R., Cuillier, B., Mud Hammer Drilling in Deep Hard Geothermal formation, from the single impact to the directional and vibration characterization, (2022) *European Geothermal Congress, Berlin*
6. Gerbaud L., Souchal R., Tarek M., (2018). Mud Hammer Drilling in Hard Formations: Bit Design Improvement Leads To Increased Rate of Penetration. *First EAGE/IGA/DGMK Joint Workshop on Deep Geothermal Energy, Strasbourg, France, (2018)*.
7. Gnirk, P.F., and J. B. J. Cheatham. (1965), An experimental study of single bit-tooth penetration into dry rock at confining pressures of 0 to 5000psi. *SPE Journal*, 5: 117–130
8. Haimson B., (1966), High velocity, low velocity and static bit penetration in tennessee marble, *Master's thesis, University of Minnesota, Minnesota, United States*
9. Han, G.; Bruno, M., (2006), Lab investigations of percussion drilling: from single impact to full scale fluid hammer, *American Rock Mechanics Association, ARMA-06-962, ARMA*
10. Hartman, H., (1959), Basic studies of percussive drilling, *Mining Engineering*, 11: 68–75
11. Hokka, M., J. Black, D. Tkalich, M. Fourmeau, A. Kane, H. Hoang, C. Li, W. Chen, and V.T. Kuokkala, Effects of strain rate and confining pressure on the compressive behavior of kuru granite. *International Journal of Impact Engineering*, (2016), 91: 183–193.
12. Jaeger, J.C. & Cook, N. G. W. (1979). *Fundamentals of Rock Mechanics*. 3rd edition. xix 593 pp., numerous figs. London: Chapman and Hall. ISBN 0 412 22010 5. *Geological Magazine*, 117(4), 401-401.
13. Liao, Rongqing A., Wu, Jiang T. (1994) New Nozzle To Increase Drilling Rate by Pulsating Jet Flow, *IADC/SPE Drilling Conference, SPE-27468-MS*
14. Ma, H., Yin, L., Ji H., (2011), Numerical study of the effect of confining stress on rock fragmentation by TBM cutters, *International Journal of Rock Mechanics and Mining Sciences*, Volume 48, Issue 6, Pages 1021-1033
15. Nguyen V.H., Gerbaud, L., Souchal, R., Urbanczyk, C., Fouchard C. (2016). Penetration rate prediction for percussive drilling with rotary in very hard rock. *Vietnam Journal of Science and Technology*, C. Vol 54 No 1
16. Souchal R., Gerbaud L., Tarek M., (2017). High-Power Mud Hammer: A Promising Solution for Hard Formations Drilling. *Abu Dhabi International Petroleum Exhibition & Conference*, Abu Dhabi, United Arab Emirates
17. Xue, L., Li, B., Wang, Z., and Bangjun L.. Ultrahigh-Pressure-Jet-Assisted Drilling Technique: Theory and Experiment. (2012) *J Can Pet Technol* 51 (2012): 276–282