Novel drilling technology combining hydro-jet and percussion for ROP improvement in deep geothermal drilling

Our ambition

Geothermal energy is expected to play a key role in addressing the climate crisis by reducing CO2 emissions related to heating and electricity generation. It offers a clean, sustainable, and non-intermittent energy source. However, drilling operations represent over half of the total investment cost in a deep geothermal project. Reducing drilling costs will make geothermal energy economically viable by lowering capital expenditures (CAPEX) and associated risks. The primary factor influencing drilling costs is time, driven by several aspects such as the lifetime of the drilling tools, tripping time, but primarily, drilling speed, i.e. the Rate Of Penetration (ROP).

The ORCHYD project addresses this challenge – the ROP drastically decreases when drilling hard crystalline rocks at depths beyond 4 km. From the outset, ORCHYD set an ambitious goal: increase the ROP by a factor of four compared to the conventional drilling techniques. To achieve this, a combination of two mature technologies is investigated: High-Pressure Water Jetting (HPWJ), and percussion drilling. The developed system benefits from the stress release process induced by an optimal combination of the grooves created by the HPWJ and the bottomhole profile generated by the drill bit.

The project consortium comprising 6 organizations from 5 nations in the EU, the UK and China has complementary expertise, ranging from theoretical and numerical approaches to manufacturing and experimental investigations. This brochure outlines each development phase, from simulation and optimization of individual processes to the final full-scale prototype testing conducted on an experimental drilling facility in Pau, France – managed by the project leader, Mines Paris.

Stress-release principle

The ORCHYD project targets the drilling of crystalline rocks located at depths greater than 4 km, such as granites, where conventional rotary drilling technologies achieve ROP as low as 1-2 m/h. Percussive drilling has already demonstrated significant improvements in drilling shallow, less-confined hard rock formations, which exhibit a degree of brittleness making the hammering process suitable and efficient. This project aims to further enhance this potential by combining percussion with high-pressure water jetting, harnessing the advantages of both rock cutting principles. The HPWJ is used to slot a groove at the bottomhole while drilling through a nozzle located at the periphery of the drill bit. This groove relieves the rock, in the immediate vicinity of the bit's action, from stress concentrations, emulating shallower depth conditions. This reduction in the rock's confining state lowers the energy required to break the rock, thereby increasing the drilling efficiency.

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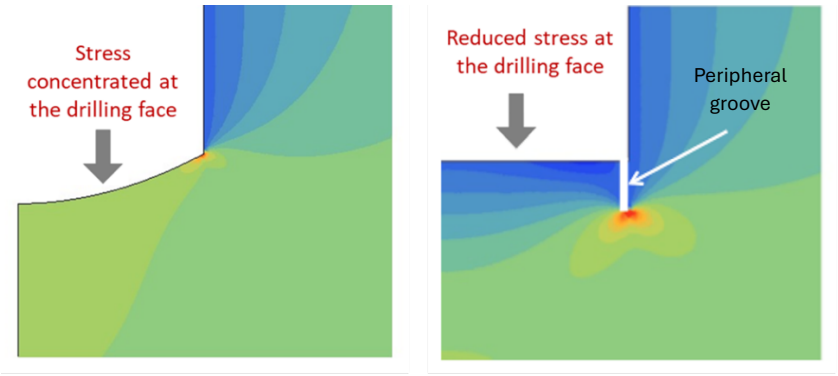
This concept is called self-relief drilling patented by ARMINES. To better understand the different phenomena and the parameters involved, numerical simulation studies and experimental validations were conducted during the project.

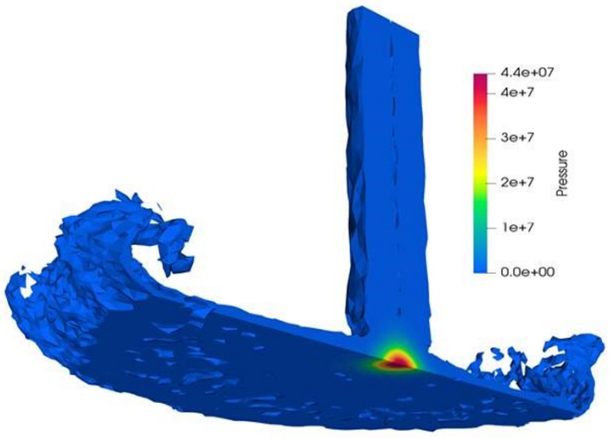


Principle of the stress release process

Jetting simulation and optimization

One of the primary research threads in the ORCHYD project is to study the HPWJ grooving process in submerged downhole drilling conditions, with the aim of identifying optimal nozzle designs and fluid pressure conditions for effective cutting in hard crystalline rocks at great depths. Findings from the Imperial College London (ICL) team indicate that the jet's destructive power is maintained within a range of 7 to 10 nozzle diameters from the nozzle outlet, requiring jet velocities exceeding those of typical bullets. Achieving such high velocities requires narrow nozzle orifices and amplified fluid pressures in the nozzle chamber, far beyond the ambient mud pressures at the bottomhole (up to 50 MPa in ORCHYD target).

Computational Fluid Dynamics (CFD) simulations were carried out to study jet formation, fluid pressurization, and impinging pressure on rock surfaces. These simulations helped optimize the parameters for effective jetting under deep drilling conditions. To model how the small (~1 mm) jet interacts with coarse-grained crystalline rock, ICL developed a rock destruction model calibrated using micro-indentation and miniature Brazilian Disc tensile tests. This model simulates the removal of rock fragments up to approximately 5 mm deep under the pressure of the traversing jet. While these models are computationally intensive and run for short distances and time intervals, they provide critical insights into the challenges of cutting significant grooves, informing the development of the hybrid drilling technology.



CFD simulation to visualize the jet pressure created by high pressure nozzle

Simulation and optimization of the percussion process

A multiscale modeling study was conducted by SINTEF and ICL to optimize percussive drilling under deep geothermal conditions by studying rock breaking at both the mesoscale (entire drill bit) and microscale (single insert level). First, finite element (FEM) and finite-discrete element (FDEM) models confirmed that grooves enhance rock breaking efficiency, with fracturing behavior

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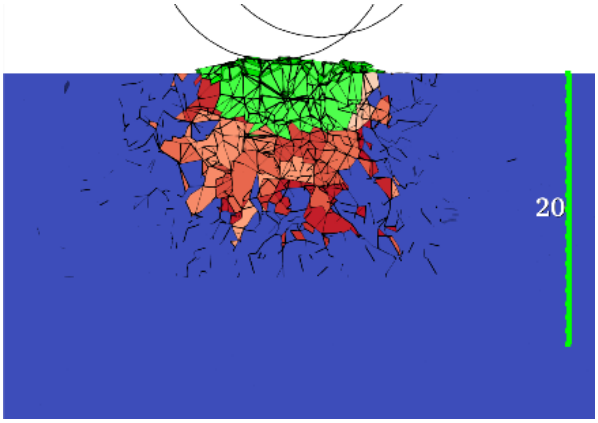
being dependent on the bit profile. To model rock behavior at mesoscale, ICL developed an experimental-FE-machine learning method that analyzes the influence of rock microstructure on rock breaking process. Algorithms were designed to generate representative rock microstructures, enabling the creation of insert-rock models that integrate the rock's microstructural properties into a macroscopic framework.

Additionally, the project investigated the dynamic response of the drilling system, focusing on the Bit Rock Interface (BRI), which contributes to nonlinearity and vibrations in the drillstring. Parametric simulations were conducted to analyze the relationships between intensifier displacement, hammer-intensifier interaction, damping and drilling parameters. The influence of the BRI on downhole drilling dynamics influenced the design of a hybrid HPWJ-percussive drilling prototype. Numerical investigations identified an optimal Weight on Bit (WOB) to enhance energy transfer, maximize ROP and control drillstring vibrations required to activate vibrational-type intensifier systems. The results clarified the choice of intensifier as discussed further.



FDEM simulation to visualize rock breakage at microscale using inserts

Laboratory tests conducted by ARMINES and SINTEF evaluated the mechanical properties of various granite types, establishing a data framework to support model calibration. A comprehensive hard rock database was developed, consolidating data on rock mechanical properties and tool-rock interaction behavior, which will be used for future refinement of percussive-jet drilling technologies.

Drilling fluid additives

The selection of an appropriate drilling fluid (mud) is critical for drilling operations. In ORCHYD's tool, mud has several purposes. As in any drilling operation, the mud removes cuttings from the drilling, maintains the required bottomhole pressure and stabilizes the wellbore. Another key function is jetting: In the intensifier, a portion of the mud flow in the drillstring is diverted and pressurized to ultra-high levels to slot a groove in the rock. Finally, the energy from the mud flow generates percussions within the MudHammer.

In order to improve drilling fluid performance, a characterization study of various environmentally friendly additives was conducted at SINTEF laboratory. Various properties such as viscosity, friction reduction, wear reduction, filter cake and thermal stability have been studied. Results highlighted the potential of using graphene oxide modified with hybrid nanosilica.

Design of a new intensifier for high pressure generation

To generate ultra-high pressure, an intensifier is used, diverting approximately 10% of the mud flow and increasing its pressure by a specific factor. Intensifiers are already used in oil and gas drilling applications, with two main types: one leverages axial drillstring vibrations, and the other is driven by a screw motor. The first one pressurizes fluid by harnessing the high amplitude axial vibrations that occur in the drillstring when drilling with a roller cone bit under high weight on bit. This system offers two advantages: it creates high-pressure water jetting to improve the ROP and stabilizes the drillstring by absorbing the detrimental axial vibrations.

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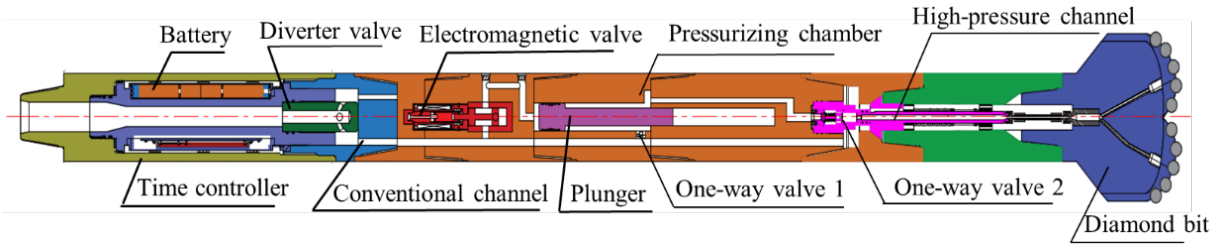

Design of the intensifier developed in ORCHYD

However, it proved ineffective when combined with a MudHammer, as the hammer generates high-frequency but low-amplitude oscillations. The screw motor-driven intensifier, on the other hand, converts hydraulic energy into mechanical energy, driving a plunger to produce an ultra-high-pressure jet. It requires high flow rate and produces pulses of short duration only.

To improve jetting efficiency, a third type of intensifier was developed within the ORCHYD project, where flow and piston movements are regulated by an electromagnetic valve. This design provides a longer-duration high-pressure jet, making it more suitable for rock slotting applications.

Adaptation of the MudHammer

Drillstar's MudHammer is a high-power, mud driven downhole hammer capable of delivering high frequency impacts dozens of times per second. It operates in combination with a specifically designed hammer bit, built to withstand high-energy impacts, unlike roller cone or PDC bits. The mud flows through a valve that regulates the flow to the piston chamber, creating percussion impacts at an adjustable frequency . For this project, the MudHammer was modified to be enable the high pressure generated by the intensifier to pass through to the bit without affecting its functionality.

In combination with the MudHammer, hammer bits were developed for the ORCHYD project. These bits required specific adaptations to accommodate the high-pressure nozzle and were further optimized based on simulation studies of both jetting and percussion. Detailed specifications for the developed hammer bits are provided in a separate spec sheet, available at www.orchyd.eu.

Testing of individual processes

Three rock types have been identified as representatives of the ORCHYD drilling target: Kuru Grey, Red bohus, and Sidobre granite. They are among the hardest granites available in quarries. To validate the stress release concept, calibrate the simulations, and evaluate performances, tests have been performed throughout the project at ARMINES laboratory. Several test cells and drilling benches were adapted to carry out specific tests involving ultra-high-pressure jet. Powerful external pump was used to generate high-pressure water jets at 250 MPa.

MudHammer

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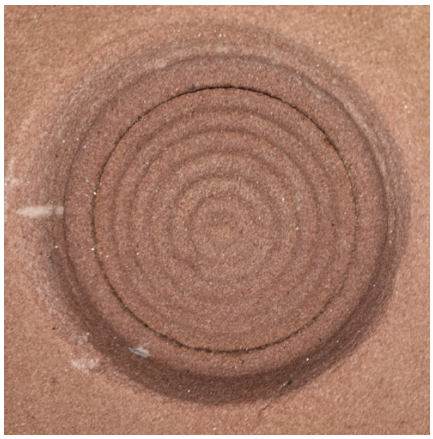
At an early stage of the project, the stress release process was validated experimentally by combining percussion and HPWJ to drill through Sidobre granite. A 170 % increase in rate of penetration was achieved when compared to percussion alone.

Jetting tests were conducted on a rock sample placed in a pressurized cell, reproducing deep drilling conditions. This approach facilitates a better understanding and optimization of the groove cutting process, as well as the calibration of the simulation models. Similarly, single impact tests were conducted with single insert or two neighbouring inserts to understand the interactions between inserts placed on the hammer bit.

Later, to better understand the combined effects, single impact percussion was tested near an existing groove, also under deep drilling conditions. Knowing the interaction distance and understanding the effect of reflected waves at the groove, allowed to optimize the insert placement around the jetting nozzle on the bit. Conversely, investigations were also conducted on slotting near existing impact craters, although no significant effects were observed.

Vertical drilling test rig in Pau, France

Moving from elementary impact to full size bit was conducted on ARMINES vertical bench, with a rock sample placed in a cell reproducing the pressure and stress conditions at depths, and the MudHammer to generate percussion. Several bit designs were tested, demonstrating great improvement from the initial design at the beginning of the project to the latest iteration, which benefited from optimization, simulation, and experimental work. Key aspects such as junk slots for flushing cuttings, insert placement, insert shape, and position and number of nozzles were thoroughly investigated, highlighting the potential of mastered bit design on the drilling performances. A comparison with a roller cone bit, commonly used in drilling at great depth, revealed greater than 4X increase in ROP when using percussion assisted with HPWJ with the optimized drill bit.



Borehole profile of a sandstone sample drilled with the ORCHYD prototype

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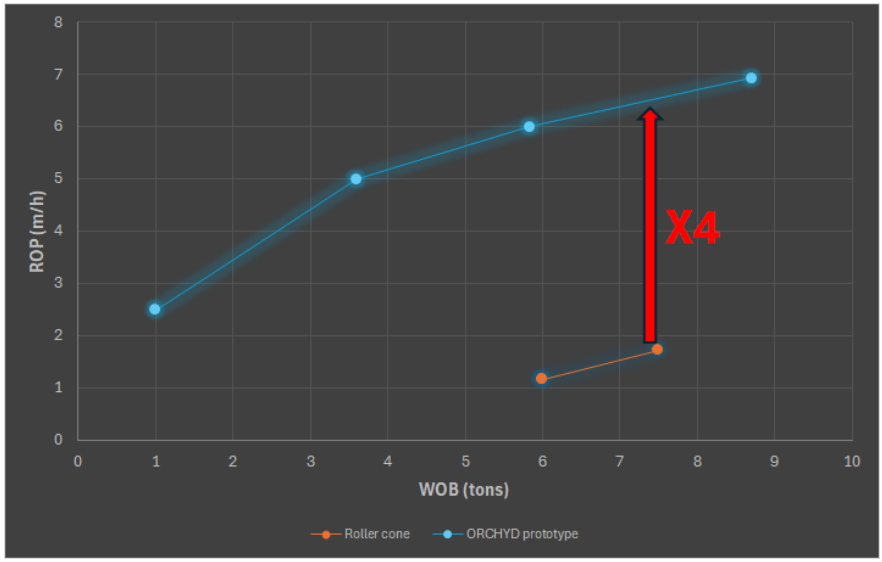

Performance of the ORCHYD prototype with respect to conventional rotary drilling tool

Experimental demonstration of the full-scale prototype

The final phase of the ORCHYD project focused on validating the novel drilling technology that integrates HPJW and percussion to enhance the ROP in deep geothermal drilling. The key components: the intensifier, the MudHammer, and the drilling bit were successfully assembled into a single drilling system prototype. Both the low-pressure and the high-pressure mud flow channels are connected through the MudHammer, all the way to the bit.

Horizontal test rig to demonstrate ORCHYD prototypes

This configuration was tested to verify the feasibility of combining high-pressure water jetting with percussive drilling. The tests have been conducted using ARMINES' horizontal drilling bench, which allowed for a longer BHA (Bottom-Hole-Assembly), and a precise control over drilling parameters to evaluate the system performance. The assembled system demonstrated its capability to generate a HPWJ while maintaining effective percussive drilling. The horizontal bench tests included drilling trials in different rock types, where the system showed cutting efficiency and good penetration rates.

Environmental and social sustainability

Another key aspect of the project was the environmental and social sustainability study carried out by University of Piraeus Research Center (UPRC). This study successfully assessed the environmental, social, and energy security impacts of advanced geothermal drilling technologies, as the one developed in ORCHYD. The project began with an Environmental Impact Assessment (EIA), evaluating the effects of faster drilling techniques on various environmental spheres, including the atmosphere, hydrosphere, lithosphere, and biosphere, using methods such as Risk

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Analysis (RA), Life Cycle Analysis (LCA), Carbon Footprint (CF), and Ecological Footprint Analysis (EFA). Social attitudes were examined through an online survey, shedding light on public acceptance of geothermal energy and how these technologies address societal needs. The energy security implications were also analyzed through the development of an energy security index, which compared the benefits of advanced geothermal drilling with conventional methods. Finally, expert interviews provided geopolitical insights, highlighting the potential of geothermal energy in strengthening global energy security and contributing to climate change mitigation. The project's findings underscore the environmental and economic viability of geothermal energy as a stable, carbon-neutral resource.

Moving forward

Overall, this research provided valuable insights and fundamental knowledge for optimizing the percussive-jet drilling process, leading to the design and development of a more efficient drilling system capable of handling the high-stress environments encountered in deep geothermal operations.

The experimental demonstration of the full-scale prototype confirmed the feasibility and effectiveness of the hybrid HPWJ-percussive drilling technology. Testing demonstrated a significant increase in the rate of penetration in hard crystalline rocks, validating the synergy between high-pressure water jetting and percussion. This combined approach has the potential to significantly reduce drilling time and costs in deep geothermal applications.

The next steps involve further refining the system for real-world field deployment, where it can be tested under real geothermal conditions. Additionally, exploring the adaptability of the technology for other applications will widen its potential impact. Whether or not the hybrid HPWJ-percussive system developed in ORCHYD is adopted as-is, the project enabled a significant improvement in the understanding of deep drilling, under high pressure downhole regime, at several levels, including bit-rock interaction, jet slotting, high pressure generation or hammer bit design, contributing to faster, more efficient, and reliable drilling operations. Beyond its technical advancements, the hybrid HPWJ-percussive technology has the potential to significantly contribute to the global transition toward sustainable energy. By improving the efficiency and lowering the costs of deep geothermal drilling, this innovation could accelerate the adoption of geothermal energy as a reliable, carbon-neutral alternative, helping to reduce CO2 emissions and combat climate change.

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