Novel concepts to construct cost effective geothermal wells with Electro Pulse Power Technology

DeepLight

Description of the calibrated EPP hydraulic model

D4.1

GEOTHERMICA

Smart Energy Systems ERA-Net

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Executive Summary

The DEEPLIGHT project is developing Electro Pulse Power (EPP) drilling technology. EPP is a novel non-mechanical rock-breaking method that unlike conventional rotary drilling, uses ultra-short high-voltage electric discharges between electrodes to fragment rock. The EPP rock-breaking mechanism results in rock fragments with a wider spread in size and shape compared to conventional drilled cuttings. To assess the viability of EPP drilling in geothermal wells, it is paramount to investigate the requirements to remove cuttings from the well and optimize fluid conditions during drilling.

A semi-empirical physics-based model was built applying the typical hole cleaning formulas used in conventional drilling. The model was adapted to the EPP cuttings characteristics and drilling fluids. A test set-up, so-called “cuttings flow loop” at TNO’s Rijswijk Centre for Sustainable Geo-energy, was used to perform a series of test. A dedicated test matrix was designed to investigate the impact of various operational parameters on hole cleaning. For example, both water and a viscous fluid were used to simulate drilling mud of different rheologies, while sand cuttings of varying sizes and concentrations were injected to investigate their behaviour under different flow regimes, inclinations and pipe rotations. The flow loop’s transparent outer pipe made it possible to visually understand what leads to the formation of the cutting beds and how the various cutting transportation regimes could be linked to the measured pressure drop over the pipe. The tests ,their results and implication for mud selection are described in Deeplight deliverable D4.2 “Flow test results and design/operational considerations for mud selection in EPP drilling”

The calibrated model can predict hole-cleaning quality based on minimal measurements, i.e. pressure. Furthermore, the model can be used to lower the power requirements for hole cleaning. The findings will be used as design input for further tool development and broader implementation of EPP technology in geothermal energy projects. This will facilitate faster, more energy-efficient, and lower risk well construction in hard-rock environments.

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Abbreviations

Abbreviation	Description	Comment
BHA	Bottom Hole Assembly	
CFD	Computational Fluid Dynamics	
CwD	Casing while Drilling	
EPP	Electric Pulsed Power	
ROP	Rate of Penetration	
RPM	(Pipe) Revolutions per Minute	

1 Introduction

An international consortium is developing a novel drilling tool based on the Electric Pulsed Power (EPP) technology in the DEEPLIGHT project. The innovative rock-breaking mechanism uses ultra-short high-voltage pulses to break a rock instead of mechanical forces based on torque and weight on bit. This method creates new opportunities to lower drilling costs, especially in very hard rock formations which are challenging to drill efficiently with conventional drilling equipment. The low mechanical loads required for drilling enable other possibilities for improvement such as higher reliability and more freedom in shaping the rock cutting interface.

For efficient hole making it is essential that the created cuttings are efficiently transported out of the hole. Poor cuttings transport, or poor hole cleaning, has many downsides that will affect the EPP tool effectiveness:

1. Stuck pipe while drilling or running casing because of cuttings beds may result in loss of the hole or the drilling assembly
2. If not completely stuck, the cutting beds may cause pack-offs that can cause formation damage, wellbore instability and pressure spikes damaging downhole or surface equipment. This may even lead to well control risks.
3. Regrinding cuttings will reduce the Rate of Penetration (ROP) and may drastically reduce the EPP rock breaking mechanism efficiency
4. Regrinding will also deteriorate the drilling fluid with more fine solids causing BHA wear, higher pressures and further reducing hole cleaning

A better understanding of hole cleaning quality for EPP operations is important during operations but also during the engineering phase, both tool development as well engineering, to ensure that the tool fits the drilling environment. The approach in DEEPLIGH project to identify hole cleaning requirements for a novel EPP drilling technology was two-fold: modeling and experimental validation. Initially, an optimized hole cleaning model was developed based on existing theories and adapted to the specifics of EPP drilling. Subsequently, experiments were conducted on the cutting flow loop (Figure 1) at Rijswijk Centre for Sustainable Geo-Energy (RCSG) to generate relevant data, which were used to validate and optimize the model.

Figure 1. Cuttings flow loop at TNO's Rijswijk Centre for Sustainable Geo-Energy used for experiments.

The drilling environments described in DEEPLIGHT deliverable D1.2, (Sosa-Massaro & Van Og, 2024) are being used to define the modelling scope, i.e. water-based fluids and both vertical as deviated well sections.

This document is part of the deliverables of work package 4 of the DEEPLIGHT project and describes the model development and calibration of the EPP cuttings transport in the annulus only, and not the cuttings transport around the electrodes. The experimental setup, results, hole cleaning around the electrodes, and conclusions are described in DEEPLIGHT deliverable D4.2 (Blinovs, Battistutta, & Van Og, 2025). The work package 4 work has been presented and published at the European Geothermal Congress 2025 in Zurich (Battistutta, et al., 2025).

2 Model selection

Various commonly used hole cleaning models have been reviewed and can be divided in the following types:

1. Analytical
2. Empirical
3. Numerical (CFD)
4. Hybrid (incl Machine Learning)

Analytical models have been improved well over the years and can accurately predict many relevant aspects of hole cleaning. They are practical but the slip-velocity and erosion correlations are usually calibrated to 'conventional' cuttings and fail for very different particle properties, i.e. particle size and shape, such as generated by the EPP rock breaking mechanism, see Figure 2. Also, odd geometries as used in Casing while Drilling, a technology which will most likely be used in combination with EPP, are generally not well captured in conventional models due to the relatively large surface areas. The analytic models fall short on accurate and dynamic cuttings bed behaviour in turbulent flow due to simplified physics. The same applies for transients and changing parameters especially in (high) inclined well bores. The long well bores with changing parameters along the well, as geometry, cutting loading density or temperature, limit the usage of analytic models. An overview of the influence of the various parameters on hole cleaning and hydraulics is shown in Table 1 .

Figure 2. The main figure shows a sample of cuttings generated by EPP rock breaking, the larger cuttings being over 2 cm large. The smaller figure on the top right displays a microscope image of the sample within 1.4- and 2-mm size.

Empirical models are very fast and practical but have limited application outside their validation domain i.e. experimental conditions. hence not useful for accurate modelling in the complex EPP environment.

In theory, the most complete and accurate method to model hole cleaning in EPP drilling operations is Computational Fluid Dynamics (CFD) because it can deal with complex geometries, has very high spatial and temporal resolution, and captures complex physics. However, CFD is slow due to the computing time but also the large amount of data required and therefore not suited for (real-time) drilling operations with continuously changing parameters. CFD is useful to gain insight in local and well-defined problems.

A hybrid model is pragmatic and covers both operational as engineering requirements. The base will be an analytical model to cover the physics which will be adapted with empiric EPP specific data using Rijswijk Centre for Sustainable Geo-energy's (RCSG) flow loop (Figure 1)**Error! Reference source not found.**. According to (Al-Rubaii, Al-Shargabi, Al-Shehri, Alyami, & Minaev, 2023) and shown in Table 1, the most relevant parameters to vary are hole angle, flow rate, pipe rotation of which flow rate has also an direct effect on the hydraulics. Indirect factors, such as cutting size, density, shape, and the ROP, which can moderately impact borehole cleaning efficiency. For example, a higher ROP doesn't directly affect the cuttings transport mechanism but creates more hole cleaning demand.

Table 1.Sensitivity of the parameters defining hole cleaning and hydraulics. According to Al-Rubaii, Al-Shargabi, Al-Shehri, Alyami, & Minaev, 2023

Parameter	Hole Cleaning	Hydraulics
Hole angle	Significant negative effect	Indirect effect
Hole size	Direct effect	Direct effect
Cutting size	Indirect effect	Direct effect
Cutting density	Indirect effect	Direct effect
Cutting shape	Indirect effect	Direct effect
Mud density	Direct effect	Direct effect
Mud rheology	Direct effect	Direct effect
Mud type	Direct effect	Direct effect
Flow rate	Significant positive effect	Direct effect
ROP	Indirect effect	Direct effect
RPM	Significant positive effect	Indirect effect
Pills	Direct effect	Indirect effect
Drill pipe eccentricity	Indirect effect	Indirect effect
Drill string size	Indirect effect	Direct effect

3 EPP model setup

The hybrid model, i.e. physics-based semi-empirical model, described by Zikovic et al. (2022) was chosen as it is already using an analytical slip velocity model adapted to an inclined flow-loop test setup and unconventional cuttings. A pressure trend analysis was used to capture the dynamic behaviour of particles in annular flow. To go beyond the trend analysis, the model was adapted from and extended to account for pipe rotation, mud type, and cuttings feed effects, i.e. ROP proxy. A rotation factor was added to the system of coupled equations, as shown below:

$$V_t = K * R * V * \sqrt{\frac{4}{3}\frac{dg(\rho_s - \rho_f \cos\alpha)}{\rho_f(C_d * \cos\alpha + C_l \sin\alpha)}}$$

$$K = k * (1 + \sqrt{(q_{cut}/10)})$$

$$R = \frac{1}{(1 + r * \omega)}$$

$$V = (\mu * \beta)^{0.2}$$

Where, V_t is terminal velocity (m/s), g is gravity (m/s^2), d is the median cutting diameter (m), ρ_s is the cuttings density (kg/m^3), ρ_f is the fluid density (kg/m^3), while K, R and V are correction factors accounting for mud type, pipe rotation and cutting feed respectively. k, r and β are correction constants, q_{cut} is the cutting feed rate (kg/min), ω is pipe rotation (rad/s), μ is fluid viscosity (cP). C_d *and* C_l are drag and lift coefficients. From the terminal velocity, the slip velocity is obtained as:

$$V_s = V_a - V_t$$

Where, V_s is slip velocity (m/s) and V_a is annular velocity (m/s). Thus, when V_a is greater than V_t, effective hole cleaning occurs, while the opposite indicates particle settling. Or, when slip velocity is negative then particle settling, when slip velocity positive then hole cleaning.

The slip velocity model is calibrated by adjusting the parameters k, r, β, C_d, *and* C_l to ensure that the model predictions match the experimental observations. The goal is to correctly predict whether cuttings are transported or settling in the annulus during stable operational periods.

4 Calibration

The modelling framework integrates automated experimental data analysis with a physics-based hole cleaning model, based on slip velocity, and pressure response, to predict and evaluate hole cleaning performance under different drilling conditions. The methodology starts with the identification of stable operational periods using a rolling standard deviation algorithm applied to flowrate, pipe rotation, and cuttings feed rate (as proxy for the drilling rate) profiles over time. Only intervals where all parameters remain constant for at least 0.5 seconds are retained, ensuring reliable input for modelling. Transient regions are excluded, and closely spaced intervals may be merged to preserve continuity. Once these stable segments are defined, and hole cleaning regime was confirmed by video, each interval undergoes detailed analysis. Average values of flowrate, pipe rotation, cuttings feed rate, and differential pressure are calculated for the duration of each segment, providing an accurate representation of the experimental conditions.

After data correction, pressure drop trend analysis is performed for each stable interval. This analysis relies on linear regression, with slopes determined by least squares fitting, to distinguish between increasing trends (cuttings settling or bed formation), decreasing trends (cuttings transport or hole cleaning), and stable trends. The strength of each trend is quantified by the coefficient of determination (R^2), which allows classification as Strong ($R^2 > 0.8$), Moderate ($R^2 > 0.5$), Weak ($R^2 > 0.2$), or Very Weak ($R^2 \leq 0.2$), see Figure 3.

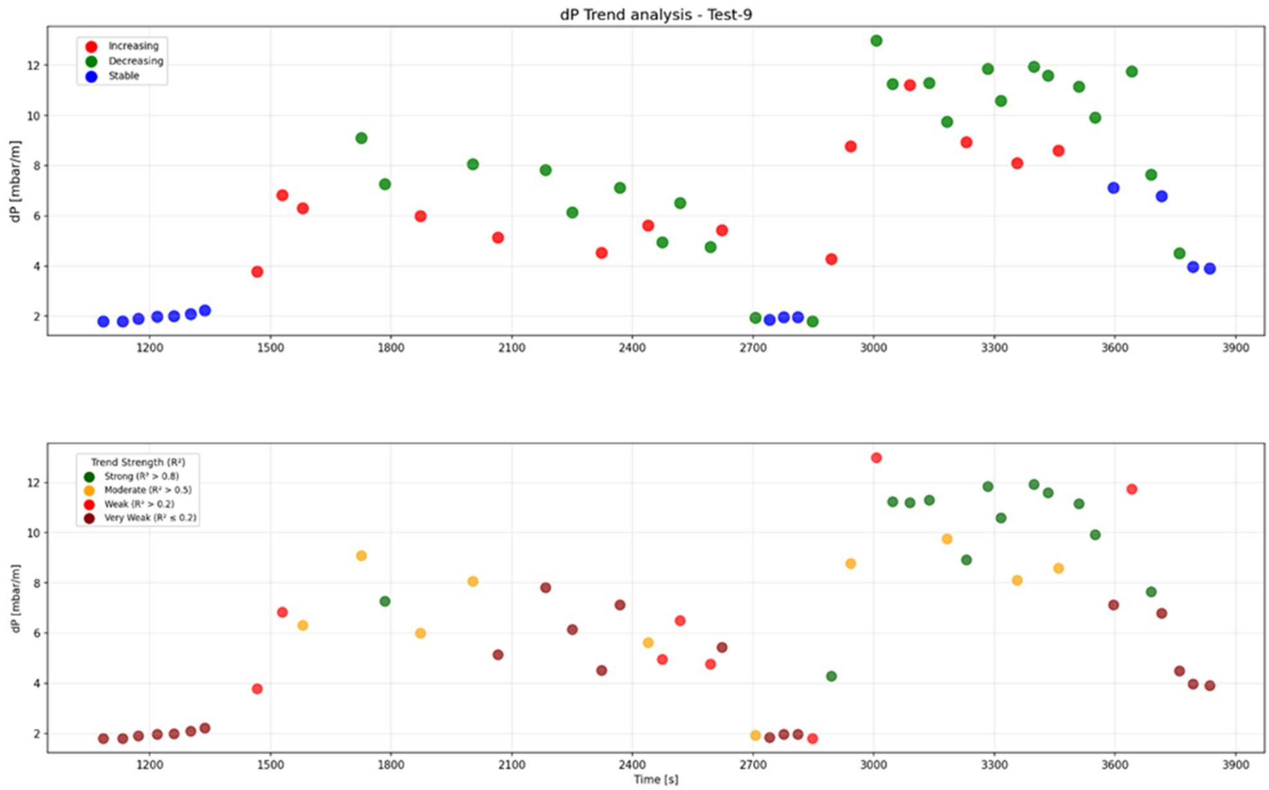

Figure 3. Enhanced pressure drop trend analysis for Test-9 showing (a) pressure trend classification with Increasing Decreasing and Stable trends, and (b) trend strength assessment using R-squared values.

Only trends with strong and moderate signal strength were used for model calibration, and the analysis provided insights into the relationship between particle transport and pressure drop response in the wellbore.

To quantify model performance, each stable interval is classified according to the model prediction and the observed pressure trend. A “true match” occurs when the model correctly predicts the cutting behavior in that interval:

- if the model predicts transport ($V_a \geq V_t$ i.e. a positive slip velocity V_S) and,
- the experimental pressure drop shows a decreasing trend,

or,

- if the model predicts settling ($V_a < V_t$) and,
- the pressure drop shows an increasing trend.

The total number of stable intervals is referred to as “total regions.” The model’s accuracy is then calculated as the percentage of true matches relative to the total regions:

$$Accuracy\ (\%) = \frac{matches}{Total\ regions} \cdot 100$$

To optimize the model parameters, multiple random initial guesses are generated within predefined bounds. Each initial set is used as a starting point for one or more of the 15 available optimization methods, including local solvers from the SciPy library, global methods such as differential evolution, and external frameworks like Optuna and Hyperopt.

The optimization process is repeated over several rounds, using different initial guesses, methods, and experimental datasets. After all runs, the parameter set that achieves the highest accuracy is selected as the optimal model. This optimal set is then applied to each individual experiment to evaluate its predictive performance.

This framework ensures that the slip velocity model is calibrated based on observed pressure trends and cuttings transport, providing a quantitative measure of how well the model captures the physical behavior of the system.

5 Experimental results

A test with water at 60° inclination and constant cuttings injection of around 5 kg/min will be used as a reference test to show the results and methodology in a qualitative interpretation of cuttings transport mechanisms and impact of operational conditions on hole cleaning (Figure 4).

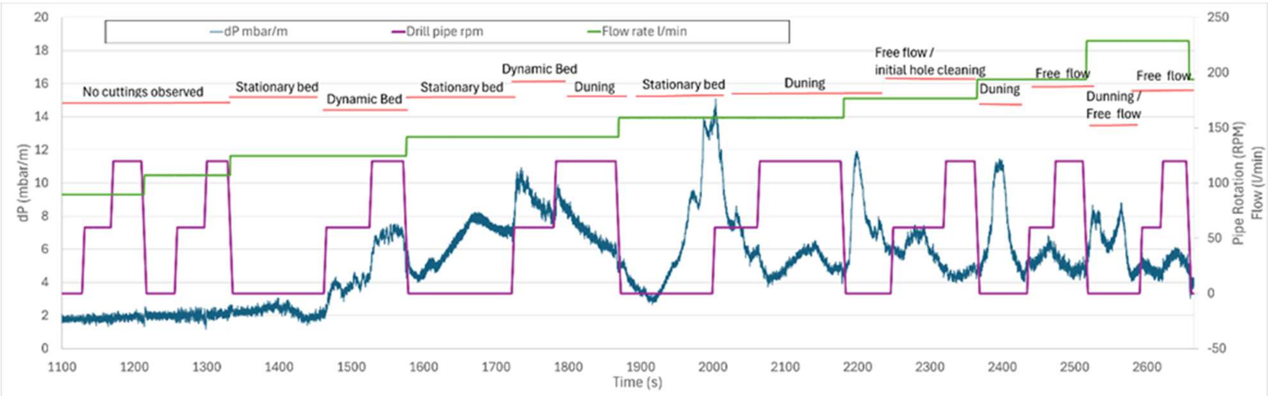

Figure 4. Example of an experiment (Test 09) using water as the drilling fluid at a 60°inclination angle. The data plotted concerned only the cuttings injection rate of 5 kg/min. The red segments report a qualitative interpretation cuttings transport regime.

Four distinct cuttings transport regimes were identified which could also be confirmed by the videos made during the experiments, see Figure 5, which proved the complexity of the hole cleaning dynamics hence the limitations of the purely analytical models.

Figure 5.Four transportation regimes at 60° test section. From top to bottom: (a) free homogeneous flow, (b) dunning, (c) dynamic bed and (d) stationary bed. The distance between the white stripes is 10 cm. Flow is going from right to left.

The four regimes can be divided as:

a) free homogenous flow,
b) dunning,
c) dynamic bed,
d) stationary bed.

At very low flow rates (89 and 107 l/min), only water circulated through the test section, and the cuttings were not effectively transported. Instead, they accumulated at the bottom of the flow loop. This situation resulted in a low, stable pressure response of water flowing through the test section where pressure sensors are positioned. At 124 l/min, the third flow rate step, cuttings began to appear and were sagged in the test section, forming a stationary bed. Increasing the pipe rotation added energy to move the cuttings bed, resulting in a sudden spike in differential pressure (dP) transitioning static bed into dynamic bed. When rotation ceased, despite an increase in flow rate, the system reverted to a stationary bed condition. Again, the rotation aided in moving the bed, and at 120 rpm the first dunes were observed (Figure 5b). This effect again ceased when rotation was reduced to 0, despite the increase in flow rate, which again resulted in forming a stationary bed. Similar trend of the impact of the rotation on the cuttings bed and pressure was observed again at 174 l/min and 60 rpm, where first indications of free homogenous flow was observed. Cuttings bed turned into dunning after decrease in pipe rotation to 0 rpm and increased flow rate to 194 l/min. The first hole cleaning without pipe rotation occurred, however, the pipe rotation further promoted cuttings removal. At the final step of flow rate increase to 230 l/min, leftover cuttings were flushed from the test section giving a sudden pressure spike followed by a stabilization in pressure. Switching on the rotation did not have major impact on the pressure curve and cuttings transport. Based on this, it can be assumed that combination of 194 l/min and 60 rpm can be used as a cut-off value for the initial hole cleaning. Converting flow rate to superficial flow velocities results in 0.74 m/s, a value that is more relevant for the actual field operation, and a reference point for the modeling study.

Transient periods occurred after the addition of the pipe rotation, and after the step increase in flow rate. The resulting pressure spikes come from a cuttings bed that is suddenly broken down, whereas the intensity of the pressure spikes depends on the size of the cuttings bed buildup. At lower flow rates (124 – 174 l/min), increase in pump flow rate was not sufficient to break the cuttings bed, although it had an effect above 174 l/min. At lower flow rates pipe rotation had predominant effect on pressure curve resulting in up to 3-fold pressure spike. The response to step increase in pump flow rate or pipe rotation can increase pressure values above the allowable ECD window, potentially fracturing the drilled formation.

7 Conclusion

Transporting cuttings out of the bore hole is an essential and a high-power consuming part of drilling. The combination of non-conventional cuttings, potentially non-conventional geometries for the case of CwD, non-stationary operations and inclined wells make analytical models fail on accurately predicting hole cleaning quality for EPP(-CwD) drilling.

A conventional slip-velocity model which was already adapted for inclination was further adapted for pipe rotation, mud viscosity and ROP. Five parameters need to be calibrated by pressure data that was acquired with TNO RCSG's flow loop in Rijswijk. Video recordings were used to confirm the hole cleaning regime as function of the flow loop parameters, mud viscosity, pipe rotation, inclination, feed rate and flow rate.

The results and final recommendations of the hydraulics and hole cleaning work in WP4 are captured in the DEEPLIGHT D4.2 report (Blinovs, Battistutta, & Van Og, 2025).

8 References

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