Machine Learning Opportunities for Geothermal Drilling Operations: An Overview

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ABSTRACT

Geothermal energy has been providing low carbon and reliable renewable resource for electricity generation since the 1950's; however, the total geothermal installed capacity comprises only 0.5% of total renewables-based capacity as of 2021, growing only ~3.5% annually. High upfront costs and resource risks associated with geothermal development proved a challenge for future investments and wide-scale adoption.

As heat is harnessed from the depths of the earth, drilling wells towards a viable resource is critical to the success of the project. Drilling has only ~83% success rate in the operation phase and accounts for 35-40% of the total capital expenditure of the project. Improving drilling performance by de-risking drilling operations will be a game-changer in pushing interest towards geothermal development.

With the recent advent of artificial intelligence (AI) technology, there is a renewed interest in looking at Machine Learning for optimising different drilling applications. Machine learning is a subfield of AI that automates the modelling of complex data sets for problem specific tasks. Combining these models with a problem specific decision model leads to AI. This paper summarises the challenges of geothermal drilling operations and gives an overview of machine learning applications in drilling operations.

1. GEOTHERMAL DRILLING HISTORY

Geothermal is a combination of two Greek words geo (earth) and therme (heat) (US Energy Information Agency, 2022), which simply translates to energy coming from the heat within the earth. Generally, temperature increases by about 25-30°C per km of depth (Fridleifsson & Lund, 2017) though it may vary across countries and their respective locations. Towards the centre is the earth's core which produces and radiates heat at an estimated temperature of ~4600°C. It is considered a renewable resource due to the continuous heat flow produced in the Earth's core. This immense energy source provides a big potential for environmentally friendly widescale electricity generation and direct utilisation and could also help in de-carbonisation efforts.

Drilling of wells to access geothermal resources is reported to have started in Lardarello, Italy, in the 1800s when holes were drilled along the vicinity of natural hot pools and fumaroles to access higher boron concentrations in the 1800s (Lund, 2005). Māoris in New Zealand also used the hot pools for household cooking, heating, and bathing until the 1800s when Europeans used these geothermal sources on a larger scale through spa baths (Stewart, 2006).

The first steam well used for electric generation was also located in Lardarello when Prince Piero Ginori Conti and consultants from the University of Pisa would successfully lit up five bulbs using a 10 kWe dynamo connected to the chosen well. (Parri & F. Lazzeri, 2016).

In the US, drilling geothermal wells for electricity generation started as early as 1921, near the Witches' Cauldron, in the Geyser Canyon, California with Well No.1 blowing up like a volcano (hydrothermal eruption) at a shallow depth. Another eventually replaced it in 1922, where steam was found at ~60m, taking the name Well No. 1. Well No. 2 was drilled to 97m in 1923 with a temperature of 153°C and 4 bar pressure. Both wells powered the first 35 kWe power plant constructed by John Grant in the 1930s, which eventually powered local resorts. (Lund, 2005;DiPippo, 2015).

In 1949, Wairakei drilled its first exploratory wells and built the 2nd power station in the world, pioneering the technology to harnessing power from wet steam (Stewart, 2006). Also in the 1950s, Japan started to drill geothermal wells, trying to find a source of hot water to supply spa. However many of the wells produced steam within 160-300m, eventually providing dry steam to Japan's first commercial power plant at Matsukawa, Honshu, in 1966 (Lund, 2005).

2. GEOTHERMAL WELLS

The geothermal "well" is drilled to serve as a conduit for reservoir fluids to the surface. Depending on use and purpose, a geothermal well may be as shallow as 20m and reach up to 5,000m. It needs to be structurally sound to contain the pressure and temperature of the drilling fluids and formation while drilling. Upon completion, it should also be able to withstand the anticipated pressure and temperature conditions during its producing life for it to be operated safely. Furthermore, its material should be capable of withstanding the reservoir fluid's characteristics during production.

2.1 Taxonomy of Geothermal Wells

Geothermal wells can be classified with respect to their purpose, diameter, and depth, which will be discussed in the following subsections.

2.1.1 According to Purpose

Typically, geothermal wells are drilled for one of five different purposes initially. It may, however, change over the course of the well's lifetime.

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Production Well – These wells act as conduits of geothermal fluids to the surface that feed into the power plant.

Injection Well – They are also called reinjection wells, where brine separated from the geothermal fluids are injected back into the reservoir for resource management.

Exploration Well – They are the first wells drilled to confirm the presence of potential geothermal resources for further development. They can be shallow, slimhole temperature gradient wells, or they can be production-ready, conventional wells.

Monitor Well – They are wells whose purpose is to house instruments which monitor the pressure and temperature condition of the reservoir. They are neither used for production nor reinjection.

Pressure Relief Well – These are wells whose sole purpose is to alleviate the conditions of a well control incident. They are drilled towards an active well to control it either by pumping water into it and collapsing the zones or pump cement into it to shut down the well permanently.

2.1.2 According to Diameter

Conventional wells are large-diameter, production-ready wells with production casing sizes ranging from 9 5/8" to 18 5/8". Production casing is the innermost casing where reservoir fluids flow. The smallest hole size typically is 6", complete with 5" perforated liners. Conventional wells require rotary drilling rig equipment to be drilled, which means larger drill sites, environmental impact, and significantly higher drilling costs. However, they can reach depths of about 2500-3000m+ due to the rig power and flexibility of the larger sizes. Drilling deep conventional wells will be the focus of this paper so that more details will be provided below.

Slimhole wells (Finger et al., 1999) – As the name suggests, is a smaller diameter drilled holes, with the smallest hole being 2"-4" in diameter. These wells are drilled to measure temperature gradients in preparation for large-scale development. Drilling slimhole wells only requires the smaller coring rigs, which require less equipment, footprint, and manpower than rotary drilling rigs, which cost lower than conventional wells. However, there will be limitations in drilling slimholes, particularly on the maximum depth it could reach due to the rig's power and tubular used in slimhole drilling.

2.1.3 According to Depth

Differentiation between shallow and deep wells may differ between countries, but generally, classification according to depth also pertains to the tapped geothermal system.

Shallow wells –Goetzl (2020) reported that shallow wells typically range at about 150m. They are economically useful for private households for direct use. These shallow wells are not intended for widescale electricity generation as the deeper wells. About 900 shallow wells have been drilled in Rotorua, New Zealand (NZGA, 2023), for water and space heating, where ~300 wells are still operating, 90 of which are <200m deep. Fluids recovered range from 120-200°C.

Deep wells – Deep wells reaching>2000m for widescale electricity generation could recover geothermal fluids up to 330°C.

2.2 Deep Geothermal Well

A typical deep geothermal well consists of two (2) major components, (1) wellhead above ground and (2) wellbore, which is a telescopic structure of cemented casings stretching kilometres deep into the ground into the reservoir. Typically, the bottom will consist of perforated or slotted liners that allow reservoir fluids to flow into the well. This production hole may sometimes be left open or "barefoot".

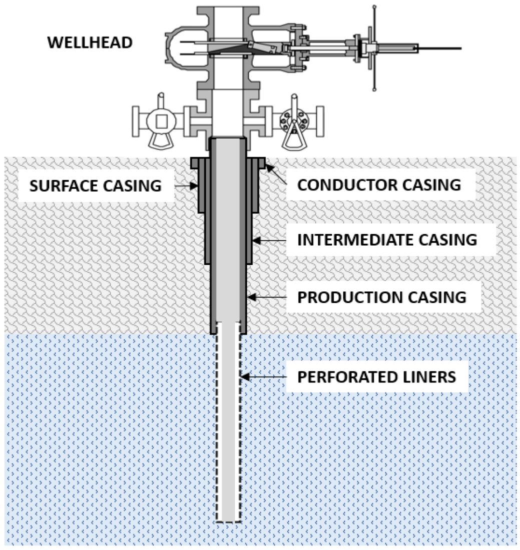

Figure 1. A typical Geothermal Well consists of a surface wellhead mounted on a series of telescopic casings extending deep into the earth

2.2.1 Parts of a Geothermal Well

Figure 1 shows a cross section of a completed geothermal well showing. Each of its major components will be discussed in detail.

Conductor Casing – The conductor casing, about 30" in diameter or greater, is typically installed before the drilling rig is mobilised to the site. Depending on the depth requirement, this casing may be pile-driven or drilled with an auger rig, spanning from a shallow 2m to a depth of 150m. It should be installed vertically to mitigate directional control issues later when drilling the main wellbore. The purpose of this casing string is only to provide structural support in drilling the next hole section and is not designed to hold any pressure. For this reason, normal line pipes and neat Portland cement may be used to optimise cost.

Surface Casing – The surface casing aims to isolate the shallow freshwater aquifer from contamination. It also isolates the shallow unconsolidated section, which is usually riddled with issues like severe lost circulation and rough drilling due to boulders. The surface casing string provides structural support for the subsequent casing strings and is also where the first blow-out preventer (BOP) is installed. In some well designs, this may serve as the primary pressure containment shoe, so the depth should be designed to handle the expected pressures, and cement integrity should also be

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considered. Also, in some designs, CHF may be installed in this string. The main considerations for choosing the setting depth are:

- Pressure containment while drilling the next section and potentially production life of well.
- Isolate shallow aquifer and unconsolidated boulders.
- Optimise directional plan or well profile.
- The volume of cement needed may serve as a capacity limitation.

Intermediate casing – A smaller diameter casing installed to case off the open hole section drilled after setting the previous casing and runs to the surface (Figure 2a). The intermediate casing aims to provide structural support for the subsequent sections. Usually, this serves as the primary pressure containment shoe. Thus, the depth should be designed to contain anticipated pressures during the lifetime of the well. This may also be the anchor casing to which the casing head flang (CHF) and wellhead are installed at the surface. For these reasons, good cement integrity is necessary for this section. There are many considerations in the depth selection for this string:

- Pressure containment while drilling the next section and potentially production life of the well.
- Isolate problematic sections like swelling clay, unstable formation, and acidic formation.
- Set prior major loss zones to ensure good cementing integrity.
- Optimise the directional plan or well profile.

Production casing – The diameter of the production casing is smaller than the previous string. It is installed to case off the open hole section newly drilled and runs through to surface. It is the casing string which is directly in contact with the reservoir fluids during production. It is designed to suit the production fluid's chemistry, pressure, and temperature characteristics. The considerations in choosing the depth for this section are:

- Pressure containment while drilling the next section.
- Set prior intersecting the reservoir section and within temperature requirements as indicated by formation minerals and characteristics.

In recent years, this section is split into two parts to drill deeper: (1) Drilling liner and (2) Tieback casing. In such completion, the open hole section is cased off and cemented first and is 'tied back' to the surface with another set of casings (Figure 2b). The liner and tied back system is used to reduce the pressure on the formation when cementing deep casings to ensure good cement job quality.

Perforated Liners – This liner set is installed in the reservoir production section.They are perforated or slotted to allow the flow of production fluids into the well. This is either set on the bottom or hung, depending on the bottom of the production casing . This set of liners provides structural support in the long term for faulted or unstable formation so as not to collapse the open holen some areas where the formation is known to be stable, drilled holes are left open for production and known as "barefoot" completion.

Wellhead – The New Zealand Standard (NZS2403:2015) for deep geothermal drilling define this as a set of valves and components installed at the surface designed to contain and handle the pressure requirements of the production fluids. It comprises the casing head flange, the master valve, and the expansion spool (optional). Wellhead may be attached to the innermost casing, which could be the tieback or production casing. It may also be attached to the Intermediate casing. Whichever the wellhead is attached to can also be called the 'anchor casing.'

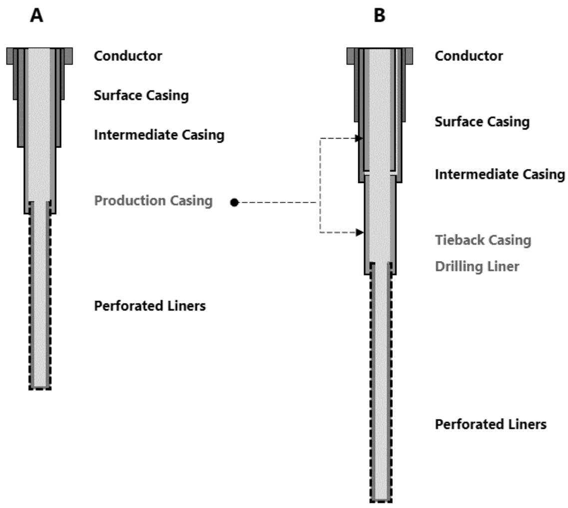

Figure 2. Typical well design's (a) production casing was split into two – drilling liner and tieback section (b) in order to reach deeper targets.

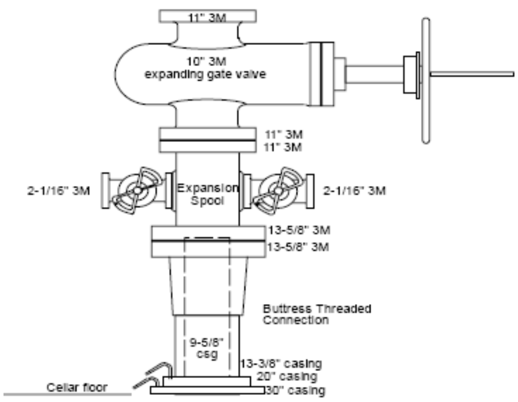

Figure 3. Expansion Spool Wellhead is one of the commonly used wellhead configuration in geothermal wells (Hole, 2008).

2.2.2 Drilling Process

A general drilling process is charted in Figure 4. There may be some variations depending on well design philosophy and objective but it all starts with the rig moving into the pad, drilling and casing off the hole, section by section until the top of reservoir is reached. The wellhead will then be installed prior drilling the reservoir section. When the permeable reservoir section is drilled, it will be secured by setting perforated liners from which the production fluids will be able to flow into the well. A completion test may be conducted to establish baseline data before or after the rig is released from the current well and moves on to the next pad.

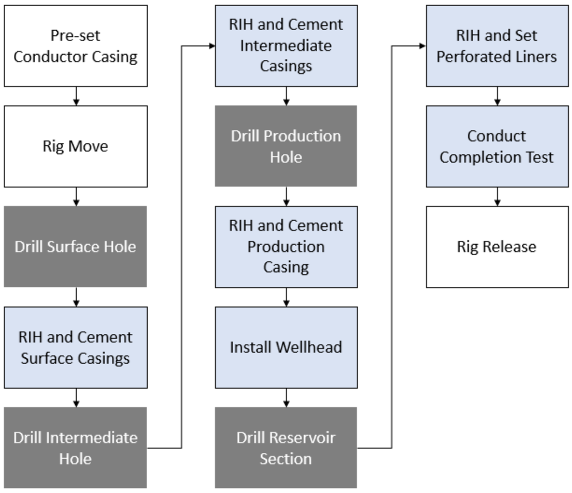

Figure 4. Simple Drilling Process begins with the rig moving in the pad, drilling and securing depths section by section until the target production zone is reached.

3. CHALLENGES OF GEOTHERMAL DRILLING

3.1 Losses

Lost circulation, whether total or partial loss of fluid into the formation, is common in geothermal drilling. They naturally occur in faulted and fractured formations, the primary targets in geothermal systems. They generally occur in the surface and reservoir sections. Surface and shallow losses are prevalent due to unconsolidated boulders, loose and highly formations. Losses in the deep section are mainly due to natural fracture systems and faults.

Severe lost circulation leads to a drop in hydrostatic pressure which otherwise supports the wellbore, placing weak formations at risk of collapse and hole instability. To mitigate this, lost circulation plugs are set until circulation is regained, allowing the drilling to continue. Depending on the area and formation being drilled, it may take up to 50 cement plugs to stop the losses. This results in non-productive time, and the rig time associated with setting these cement plugs drives up the cost of drilling.

In cases where the formation is stable, drilling ahead “blind” or with total losses is acceptable to some degree. Drilling ahead blind compromises the quality of the mud as it is a struggle to keep up with the losses when mixing new mud. This leads to more expensive materials like polymers since bentonite, the commonly used mud chemical, needs longer to pre-hydrate to attain target properties, causing the well to bloat. The pump rate volume requirement for proper hole cleaning is also high in the shallower big holes. Therefore drilling ahead blind requires a continuous supply of water, which could be challenging in some areas.

Severe lost circulation in the reservoir section is ideal, production-wise and is being targetted in most wells; however, drilling ahead blind affects hole-cleaning capabilities adversely, since the cuttings generated are not brought to the surface and remains in the wellbore instead. Improper hole cleaning can result in stuck pipe due to hole packing off with cuttings.

3.2 Swelling Clay

Clay minerals are abundant in geothermal systems. The occurrence of different types of clays can be used as geothermometers and to determine target depths at which to set certain casing strings. The progression of the clays and alterations are useful indicators to approximate the approach to a geothermal reservoir. Table 1 list clays of a typical formation and the temperature at which they can be found.

Table 1 Typical Clay Assemblage and Temperature
(Hedenquist and Arribas, 2017)

Clay	Temperature	Remarks
Smectite (Montmorillonite)	10-200C	Swelling @150C becomes interlayered with Illite
Kaolinite	<200C	Non-swelling Dispersible Acidic
Chlorite	>150C	Non-swelling
Illite	>220C	Non-swelling

Of the four different types of clays, Montmorillonite is one of the primary concerns while drilling above the reservoir, where temperatures are low enough for them to occur. Montmorillonite expands to 15× its dry volume and generates pressures in excess of 30,000 psi (2069 bar) when it comes in contact with water (Nyaga, 2021). Geothermal drilling uses water-based mud, and this causes those clays to expand, causing wellbore instability as the formation is pushed into the drilled hole – a mechanism called sloughing. These sticky clays also adhere to the drill bit in a mechanism called bit-balling, reducing the drilling efficiency and, at times, necessitating being pulled out of the hole to get rid of the clay. On some occasions, these sticky clays adhere to the drilling assembly completely, causing a stuckpipe situation, resulting in loss of drilling bottom hole assembly (BHA) and loss of hole.

3.3 Unconsolidated formation

The unconsolidated formation, also called collapsing formation, consists of a loosely packed formation with little to no bonding matrix between the particles or clasts. This type of formation issue is commonly associated with shallow sections above the top of the reservoir due to layers of sedimentary deposits over time.

Because of the nature of the formation, rock particles tend to fall into the hole when disturbed during drilling easily. These unstable unconsolidated formation needs to be supported by the hydrostatic pressure through the design of the mud to maintain stability during drilling.

3.4 Fractured and Faulted Formations

Geothermal systems are mostly formed along areas with increased tectonic activities and fault systems. High mass flows of geothermal fluids are extracted from these high permeability areas associated with natural fractures and faults. Therefore, these zones deep in the reservoir tend to be unstable since they are seismically active.

This challenge is inevitable since these permeabilities serve as the targets of geothermal wells. Drilling and cutting through a fault is challenging since it can also lead to stuckpipe situations due to loose formation. Faults also have a natural gradient that could influence the well's direction; if left uncontrolled, the drilling assembly will tend to move along the fault – this mechanism is called bitwalking.

3.5 High Temperature

Geothermal systems that can used for production need a potent heat source and good permeability. Geothermal systems can reach up to more than 300°C during production. A summary for the classification of geothermal systems according to temperature was provided by Zarrouk and Mclean (2019) in Tab. 2.

During drilling in a quenched condition, drilling temperatures may reach up to >150°C, the average temperature limit for most tools due to rubber limitations. Drilling safely and successfully under such high-temperature conditions do not only need specialised tools and equipment but also specialised personnel training. In addition, materials, including cement used in the well construction, must sustain operation at much higher temperatures throughout production throughout its useful life.

Table 2 Classification of Geothermal Systems according to Temperature (Zarrouk & Mclean, 2019)

Geothermal Resource	Low	Intermediate	High
Muffler and Cataldi (1978)	<90	90-150	>150
Ryback (1981)	<150	-	>150
Hochstein (1988)	<125	125- 225	>225
Benderitter and Cormy (1990)	<100	100-200	>200

3.6 Well Control

According to IADC (2023), a Well Control Incident is defined as a failure of barriers or failure to activate barriers resulting in an unintentional flow of formation fluid, known as a well kick.

A well kick happens when there is uncontrolled flow of geothermal fluids into the surface. Uncontrolled flow forms when the pressure of the reservoir is higher than the wellbore pressure, known as an underbalanced, allowing the fluids to flow into the well.

During drilling, the first barrier is the hydrostatic barrier, such as the drilling fluid, and then the mechanical barriers installed in the drilling rig known as a blow-out preventer (BOPe), full opening safety valve (FOSV), and inside BOP (iBOP) installed in the drill string.

Severe lost circulation, especially in the production intervals, is expected and common as such is the nature of any geothermal system. The loss of circulation leads to a drop in the dynamic water level and effectively reduces the hydrostatic support, which is well control's first barrier. Sometimes, to aid in hole cleaning, air may be introduced into the mud system to effectively reduce its mud density, thereby reducing hydrostatic pressure support. Thus, a balance between hole cleaning and well control must be in place for a safe drilling operation.

In cases where the barriers fail, and steam kicks happen, the well needs to be bullheaded with large volumes of water to collapse (quench) the feedzones. However, drilling in remote places also challenges water availability, so contingency measures should be in place to address well control scenarios.

3.7 Stuckpipe

Stuck pipe occurs when the drilling BHA cannot move up or down nor rotate. Some downhole forces prevent it from moving from its current position. Stuckpipe events mostly occur when making a new hole - during drilling, making a connection, pulling out of the hole, and backreaming. Still, they can also occur during casing running and running in logging tools.

Challenges mentioned previously can result in stuckpipe situations, arguably the most dreaded non-productive time, because it takes significant rig time trying to free the pipe with a low success rate. Furthermore, stuckpipes result in the whole BHA, including expensive tools, being left in the hole and subsequently losing the hole itself.

There are several stuckpipe mechanisms such as solid induced packoff, differential sticking, wellbore geometry and others. Their potential causes are listed in Table 3:

Table 3 Common Stuckpipe Mechanisms in Geothermal Drilling

Stuckpipe Mechanism	Common Causes
Solids Induced Packoff	Hole Cleaning
	Unconsolidated Formation
	Fractured and Faulted Formation
	Tectonically stressed formation
	Reactive Formation
Differential Sticking	High overbalance
	Porous formation
	Mud cake/filter cake
Wellbore Geometry	Ledges and Doglegs
	Keyseating
	Undergauge hole
Others	Junk in hole
	Cement blocks

4. DRILLING DATA ACQUISITION

Drilling formation several kilometers deep into the earth requires relating and understanding several different parameters from different surface and downhole instrumentations to determine the state of the hole and its general location at any given point.

Rigs have surface instrumentations to determine parameters like weight on bit, hookload, RPM, rotary torque, standpipe pressures while drilling. Drillers use trends from these parameters to analyse hole and drilling condition to make decisions on whether to drill ahead, pause and extend circulation, conduct wiper trip, or pull-out to surface. It is very essential that drillers, drillsite manager, and drilling engineers understand what these parameters signify to be able to prevent drilling issues and address them when encountered. Different interpretation at crucial situations can lead to the devastating problems discussed on the previous section

Geologists use lithologic markers or indicators from the drilled cuttings to estimate the location by determining the mineral composition and rock characteristics from drilled cuttings that return to surface.

Mud logging is the process of obtaining a detailed record or “logs” of all cuttings that return to the surface, and drilling parameters on both time and depth basis. When it was first introduced, it was only intended to record depth and the lithology of the cuttings obtained in the hopes that it contained hydrocarbons. Over the years, more sensors have been added by and around the rig to make mud logs, including drilling rig data, pit sensors, and gas sensors (Varhaug, 2015).

Mud logging units nowadays are installed to monitor drilling and geologic parameters in real-time. Mudloggers coordinate and inform the drilling supervisor when drilling breaks, losses, inflows, high temperatures, or geologic indicators are encountered which are relevant to safe drilling execution. Modern mud logs are mostly recorded in digital format, so it is easily stored, retrieved, displayed at multiple locations, and connected to other drilling software. A sample mudlog is shown in Figure 5.

Here are some surface data measurements which form part of a typical mud log:

- Depth
- Block Height
- Rate of Penetration
- Bit Depth
- Hookload
- Weight on Bit
- Surface RPM
- Downhole RPM
- Surface Torque
- Standpipe Pressure
- Pump Stroke Rates
- Trip Tank Volumes
- Mud Gain/Loss
- Mud Flow Rates
- Mud Temperature In/Out

Other sensors may be included and connected to the mud logging unit. They are as follows:

- Air injection Rate
- Backside Pumping
- Gas CO_2 and H_2S

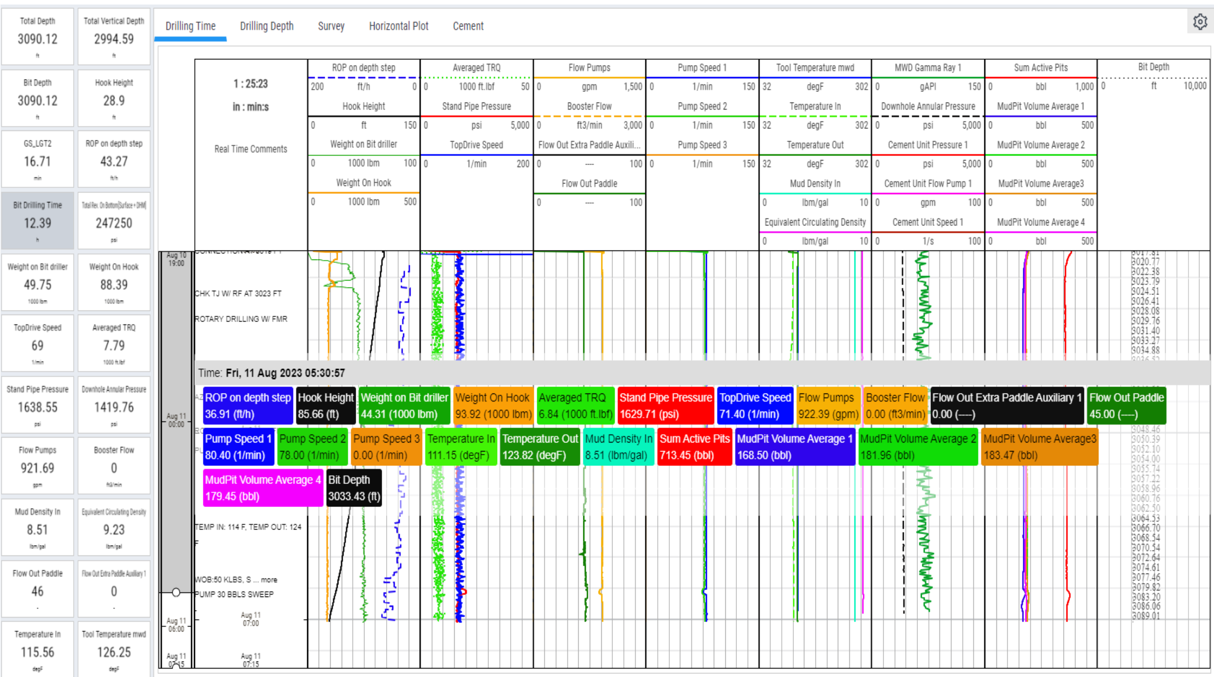

Figure 5. A Mudlog includes visual plots of drilling parameters and lithologic description per depth drilled. The mudlog is an anonymised screenshot from an actual drilling project.

4.3 Measurement While Drilling (MWD)

Drilling decisions are made based on the best available data. Surface data measurements provide adequate information compared to the geolographs, but are still limited when reservoir-related decisions are needed or when improving drilling efficiency. Information from downhole measurements coupled with the mudlogs can lead to real-time changes in drilling method, drilling direction, and casing shoe depth and possibly execute preventive measures for a possible well control issue, among others (Finger and Blankenship, 2010).

Measurement While Drilling (MWD) is simply the process of obtaining drilling data measured near the bit and transmitted to the surface without interrupting normal drilling operations (Inglis, 1987).

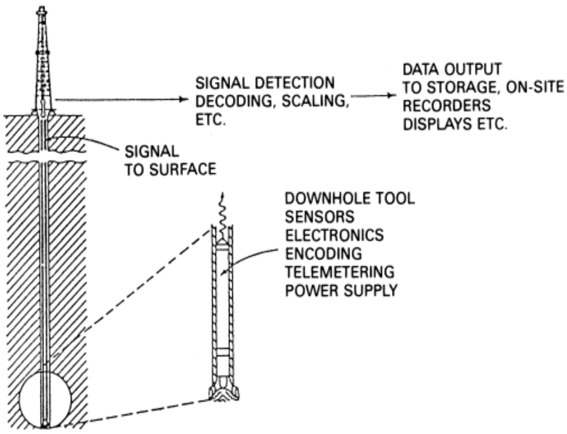

Figure 6. MWD Set up consists of a downhole sensor and transmitter powered by batteries and surface receiver to interpret signals (Inglis, 1987)

The MWD tool is mounted in the drilling assembly, acquires data through its sensors, and transmits the signal via a transmitter to the surface for real-time monitoring with the MWD surface system. The signal may be transmitted through several telemetry types depending on the condition and data being obtained – (1) electric conductor, (2) mud pulse, (3) electromagnetic, and (4) seismic or acoustic waves. Mud pulse-based MWDs have been mostly replaced by electric and electromagnetic based MWDs since the latter do not need returns to surface to be able to transmit signal.

MWD is primarily used for directional control. Corrections can be made appropriately without wasting drilling time with -a time survey of the drilling assembly direction.

However, more sensors can be added depending on the requirements. Below is some data that can be acquired using MWD with the additional sensors and probes.

Table 4 Common Data Acquired in Geothermal Wells

Category	Data Acquired
Directional control	Tool face
	Inclination
	Azimuth
Formation Properties	Density
	Porosity
	Resistivity
	Acoustic-caliper
	Inclination at drill bit
	Magnetic resonance
Drilling parameters	Downhole WOB
	Torque
	Temperature at depth
	RPM
	Tool vibration
Pressure-while-drilling	Annular Pressure
	Equivalent Circulating Density (ECD)

6. MACHINE LEARNING

Machine Learning (ML) is a subfield of Artificial Intelligence (AI). AI is the science of developing digital systems and machines to carry out tasks that would otherwise require human intelligence (Lund, 2023). AI combines machine learning models with decision models in order to automate real-world tasks.

Zhou (2021) defines machine learning as a "technique that improves system performance by learning from experience via computational methods." Mitchell (1997) provides a more formal definition for machine learning "*As a computer program is said to learn from experience E, for some class of tasks, T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.*''

Machine learning, as its name suggests, is just a "machine" (e.g. computer program, computer system, or software), which is said to be "learning". The machine learns by adjusting the coefficients of a mathematical model or the conditionals of an algorithm such that the respective task is performed as best as possible. For this purpose, numerous observations need to be quantified in order to learn from these data. The learning algorithm or model is the method by which it learns by performing tasks repeatedly. These algorithms and models are computational and thus are measurable.

Machine learning has four categories:

- **Supervised Learning** is when machine learning model is trained through a set of labeled data done by a domain expert, in order to make predictions.
- **Unsupervised learning** is when parameters are evaluated without labels, aiming to find structures and patterns to extract general rules.
- **Semi-supervised learning** is a combination of both, aiming to learn structures and patterns but also make predictions.
- **Reinforcement Learning** involves rewarding positive outcomes over negative, such that the machine learns to adjust itself to optimise rewards (Goodfellow, et al. 2016).

Deep learning is a more specific aspect of machine learning based on artificial neural networks emulating brain function to perform problem-solving and pattern-recognition techniques without human intervention (Lund, 2023).

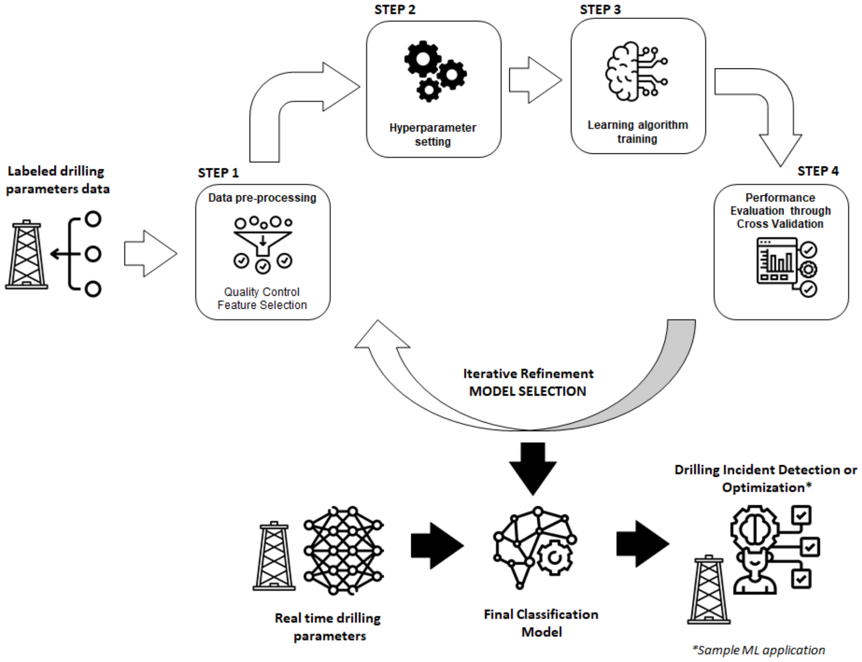

Figure 7. Machine Learning requires extensive data pre- processing techniques prior loading into the selected ML model, after which the model needs to be cross validated for fitness (Modified from Pudjihartono et al, 2022)

A typical machine learning model development lifted and modified from a machine learning study by Ben Aoun and Madarasz (2022) is shown in Figure 7.

After data is collected, the data will be split into training set and validation set. The split ratio is typically 80% and 20% for the train and validation sets. The ratio of training set to validation set may be changed depending on model design. The validation set will be set aside and will be used for model validation later on. The training data set will undergo pre-processing and will be used to develop the machine learning model. After that, the model will be used to make predictions. These predictions will then be compared to the validation set, which the model has not previously seen.

6.2 Machine Learning and Drilling

Improving drilling performance by de-risking and optimising drilling operations will be a game-changer in pushing interest towards geothermal development, where huge upfront costs prove deterrent for widescale investment. To date, the total geothermal installed capacity comprises only 0.5% of total renewables-based capacity as of 2021, and has only grew ~3.5% annually (International Renewable Agency and International Geothermal Association, 2023).

With the advent of sophisticated artificial intelligence (AI) technology coupled by massive drilling data acquisition and readily available digital format, there is an opportunity to use Machine Learning as a practical approach to addressing drilling challenges and optimising different drilling applications and target to improve the ~83% global average success rate for drilling in an Operation phase (International Finance Corporation, 2013). Machine learning has the potential to address tactical decisions during drilling execution by raising alerts when potential incidents are detected, and strategic decisions during well engineering and planning using offset wells.

6.3 Machine Learning for Geothermal Drilling

More than 60% of the available machine learning studies reviewed for this paper were conducted from 2018 onwards, although the earliest was done in 1999. Olukoga and Yeng (2021) and Zhong et al. (2022) also reviewed these studies comprehensively. Almost all of these studies were conducted on oil and gas drilling but could still provide a good benchmark on the machine learning opportunities for geothermal drilling applications. The focus areas of the 107 machine learning studies reviewed are presented in Table 5. Detailed discussion on each topic will be presented in the sub sections.

Table 5 Machine Learning Drilling Topics Coverage

ML Topic	No. of Studies	Section
Stuck pipe	17	6.3.1
ROP	14	6.3.2
Lost Circulation	14	6.3.3
Well Control	14	6.3.4
Drilling Hydraulics	12	6.3.5
Drilling Fluids	10	6.3.6
Bit + BHA	10	6.3.7
Incident Detection	7	6.3.8
Geology & Reservoir	6	6.3.9
Other	3	

6.3.1 Stuck pipe

Most of the studies are related to stuck pipe incidents and rightly so, as it is the most expensive drilling issue and happens frequently. Studies available aimed at predicting stuckpipe occurrences, stuckpipe probabilities, and identification of type of stuck pipe mechanism.

Stuck pipe is also prevalent in the geothermal application and is a potential focal point for machine learning studies, although lithologies and drilling dynamics may differ.

6.3.2 Rate of Penetration

The rate of Penetration (ROP) determines the speed of drilling; thus, a lot of energy is put into enhancing ROP to reduce drilling time, thereby reducing the well's overall costs. Consequently, a lot of machine learning studies focus on ROP prediction, identifying the drivers that increase ROP and optimise them in the future.

Increasing ROP in geothermal drilling is also ideal, but has to be balanced with other parameters since geothermal drilling is coupled with losses that could compromise hole cleaning.

6.3.3 Loss circulation

Loss circulation in drilling leads not only to lost time from the cement curing operations but also to potential stuckpipe situations arising from collapsed wellbore from loss of hydrostatic support or solids-induced hole pack off from the compromised hole cleaning capacity. Being able to predict its occurrence, estimate loss circulation probability, and even predict its rate or severity is critical and, thus, became the subject of many machine learning models. Some even attempted to identify loss circulation zone and types of solutions to address the losses.

Losses are abundant in the geothermal systems, whether in shallow or deep zones. These studies will prove valuable to geothermal drilling in addressing losses related challenges.

6.3.4 Well Control

Well-control Machine Learning studies focus on kick detection and failure of mechanical barriers, i.e., BOP. Loss of well control has a low probability of occurrence due to several mitigating measures but has a high impact because it could result in loss of lives, property and equipment. This would be the primary reason why many studies also focus on this subject.

Well, control in geothermal drilling is much less dangerous than in oil and gas drilling due to the nature of the geothermal fluids. It can still cause physical injuries and result in loss of lives, property, and equipment. It would also be essential to predict and detect any well control issue in geothermal applications.

6.3.5 Drilling Hydraulics Diagnosis

Many of the studies on drilling hydraulics predict surface pressure loss and identify drill string washout. A few tackles issues related to hole cleaning like cuttings concentration, cuttings bed accumulation, cuttings settling, and cuttings slip velocity.

Hole cleaning is a critical issue in geothermal drilling, especially when drilling deeper due to the massive losses. Machine learning relating to hole cleaning will be useful for real-time drilling decisions like extending circulation time, reducing ROP, or setting casing to avoid hole pack-off.

On the other hand, modelling pump pressure loss when it can already be read in gauges, measured remotely by sensors at the surface, may not be a compelling use of machine learning efforts and does not address any drilling challenges.

6.3.6 Drilling Fluids

Reviewed Machine Learning studies on drilling fluid deal with the prediction on its properties like mud density, plastic viscosity, yield point, API filtrate loss, and filtrate properties.

These properties, however, are measured already at the surface by the mud engineer through periodic testing of the drilling mud. Modelling drilling fluid and its properties alone do not address any drilling challenges and may not be a smart use for machine learning technology.

Instead, focusing on the dynamic change in temperature, mud weight, or solids content, among others as potential indicator for feedzones, water or gas inflow areas, and formation characteristics, may be a good ML application on drilling fluids.

6.3.7 Bit and BHA

Bit and BHA machine learning projects focus on modelling bit and BHA performance specifically, bit bounce, bit type vs ROP, bit size selection, drill string vibration, whirl, and stick-slip, among others. Improving any of these factors may result in longer depth drilled, better hole profile, and more on-bottom drilling resulting in increased overall ROP.

These machine learning studies will be useful in improving the drilling efficiency and could lead to significant savings.

6.3.8. Incident Detection

Some studies like Gurina, et al's 2020 and 2022 papers aim at detecting incidents, particularly non-productive time or abnormal drilling events. These events lead to significant lost rig time and must be minimised or eliminated. Some studies even predict the type of NPT or trouble to be encountered. With this model, mitigation measures can be placed in advance or -time decisions can bmade while drilling.

A machine learning program that detects incidents or troubles ahead of time is very valuable in any drilling operation and will be valuable or geothermal applications.

6.3.9 Geology and Reservoir

While this may be out of scope for drilling operations, some aspects of the studies could be helpful to drilling, like pore pressure prediction, porosity and permeability prediction. When done in real time, these can support decisions related to hole-cleaning capability and well control. It may also be used to fingerprint geology using drilling parameters to indicate a probable change in formation, cutting through a fault, or infer potential formation instability.

For this to apply to geothermal drilling, the machine learning study must be useful even in a total lost circulation environment to model drilling inside the reservoir.

7. CONCLUSION

High upfront capital costs and resource risks associated with geothermal development slow down widescale adoption of the technology even if it can provide a reliable baseload alternative to fossil fuels. One of the biggest drivers of this cost is the drilling of wells not only during exploration and development but also throughout the lifetime of the steam field for maintenance due to natural decline.

Geothermal drilling has a lot of inherent challenges due to the nature of the technology, mainly lost circulation, fractured and faulted formation, and high temperature. It may also be aggravated by formational issues like unconsolidated formation and swelling clays, which, if unmitigated, may result in a stuckpipe situation. Stuckpipe situations are costly, non-productive use of rig time, resulting in lost-in-hole bottom hole assembly or, worse, the hole itself. Improvement in drilling efficiency or probability of success in reaching drilling targets will reduce overall cost, thereby enhancing overall geothermal development economics.

Machine Learning, a subfield of AI that allows software applications to build algorithms based on sample data sets, "learn" from it, and eventually become more accurate over time (presented data) at predicting outcomes, provides an opportunity for drilling improvement. 60% of the existing machine learning studies on drilling that was reviewed were done in the past five years. From the papers reviewed, the main topics which would deliver the highest impact are those that address certain aspects of the challenges to geothermal drilling, like Incident Detection for Stuckipipe, Well Control, and Loss circulation. With the application of Reinforcement Learning, there may be some optimisation potential for the ROP enhancement, bit and BHA performance, if the drilling process could be simulated as a computer model itself.

Machine learning efforts to model parameters that can be easily measured by sensors, gauges, or procedures at the surface, like drilling fluid properties, drill string washout, and surface pressure losses, may not be a smart use for the technology.

Overall, the machine learning process is tedious, requires a vast amount of processed data, and multiple cross-validations of the model for it to be useful, but it also provides the level of pattern recognition, massive data handling and processing that may be difficult for humans to do consistently on a day to day basis. Such computing capabilities will be useful in drilling operations where multiple data being processed to develop suitable drilling decisions.

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