Modelling of Geothermal Cuttings Transportation During Drilling—A Case Study of Well PW-03B in Paka Geothermal Field, Kenya

Thomas Miyora, Elvar K. Bjarkason and Shigemi Naganawa

Graduate School of International Resource Sciences, Akita University, Japan

Keywords

Aerated drilling, drilling optimization, cuttings transportation, simulation, hole cleaning

ABSTRACT

The cost of a geothermal well depends heavily on the drilling time and it is crucial to minimize downtime during drilling. For geothermal wells drilled within the North Rift, Kenya, experience has shown that a higher rate of penetration (ROP) can be achieved, for example, by using polycrystalline diamond compact (PDC) drill bits instead of roller cone bits. However, operators have been hesitant to drill at high ROPs since such operation settings have been associated with an increased occurrence of stuck pipe situations. Increasing the ROP requires removing drill cuttings more effectively and at a higher rate to avoid accumulations of cuttings in the well. Firstly, accumulation of cuttings in the well annulus may result in direct mechanical sticking of the drill string. Secondly, it may also cause increased equivalent circulating density (ECD) leading to fracturing and wall collapse that can cause drill string sticking. Therefore, insufficient transport and removal of drill cuttings increases the risk of a stuck pipe.

This study targets determining optimum hole cleaning parameters for drilling geothermal wells in the North Rift geothermal fields in Kenya. The goal is to establish what drilling parameter settings are needed to enable safe drilling at the high ROPs that have been shown to be achievable. This work explores optimal hole-cleaning parameters based on numerical simulations that are supported by field observations. The authors have modified a transient cuttings transport (TCT) simulator to model cuttings transport for a well drilled in Paka geothermal field, Kenya. The simulations describing a moderately inclined well account for the cuttings concentration, slip velocity, characteristic of the ECD and phase velocities characteristics. Aerated drilling fluid was considered in the simulations.

1. Introduction

Most geothermal formations are highly altered and fractured and loss of circulation during drilling is common. The choice and design of drilling fluids is essential to ensure that the downhole conditions are maintained at optimum operating conditions to minimize problems. Azar and

Samuel (2007) stated that most common problems encountered while drilling include the following:

- Stuck pipes
- Lost circulation
- Hole deviation
- Pipe failure
- Borehole instability
- Mud contamination
- Formation damage
- Insufficient hole cleaning
- H2S-bearing formations
- Equipment and personnel related problems.

Each of the problems stated above can be dealt with according to drilling engineering practices. Careful analysis of these problems shows that most of the issues are closely related to hole cleaning. Hole cleaning performance depends on aspects such as the drilling fluid properties, drilling fluid velocity, geometric characteristics of the well, cuttings characteristics, the drilling penetration rate, and the annulus/pipe eccentricity. Stuck pipe may either be differential or mechanical and is closely related to hole cleaning. Improper hole cleaning in deviated holes will lead to drilling problems. Borehole instability, mud contamination, formation damage and lost circulation may be linked to hole cleaning and drilling fluid design.

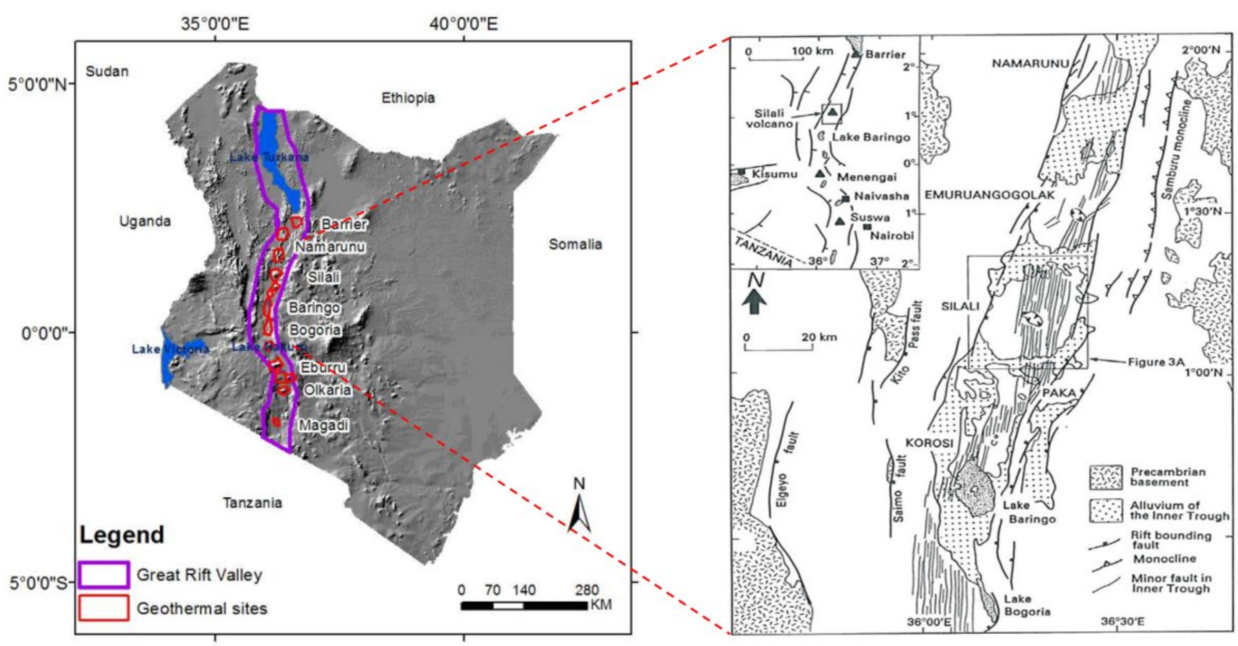


Figure 1: Locations of geothermal prospects in Kenya. The zoomed part shows the Korosi, Paka and Silali geothermal fields. Adapted from Mary et al. (2017) and Marietta (2012).

In recognition that these problems have a big impact on the time taken to drill the well and by extension the overall cost of the well, designing effective cuttings transportation parameters is imperative in alleviating the problems (Azar and Samuel, 2007). This study looks at modelling of hole cleaning parameters for wells drilled within the Paka geothermal field in Kenya. The model will later be used to obtain optimal hole cleaning conditions through analyzing drilling performance data from a well recently drilled in the Paka field.

2. Drilling in Paka Geothermal Field

2.1 Drilling History of Wells in the Paka Field

Paka geothermal field is one of the many geothermal fields found within the Kenyan Rift valley, towards the Northern side. Exploration drilling in Paka started in December 2018 by drilling well PW-01. As of June 2023, 14 wells had been drilled in Paka geothermal field. Figure 1 shows the relative position of Paka geothermal field.

Figure 2 compares the time taken to drill wells within the Paka geothermal field. The plot shows how drilling of recent wells, especially well PW-03B, has progressed more rapidly than earlier wells. Drilling could however not proceed beyond 2791 m because high torque and drag forces that exceed the drill-pipe design limits were experienced. Overcoming this challenge is one of the motivating factors for carrying out this research.

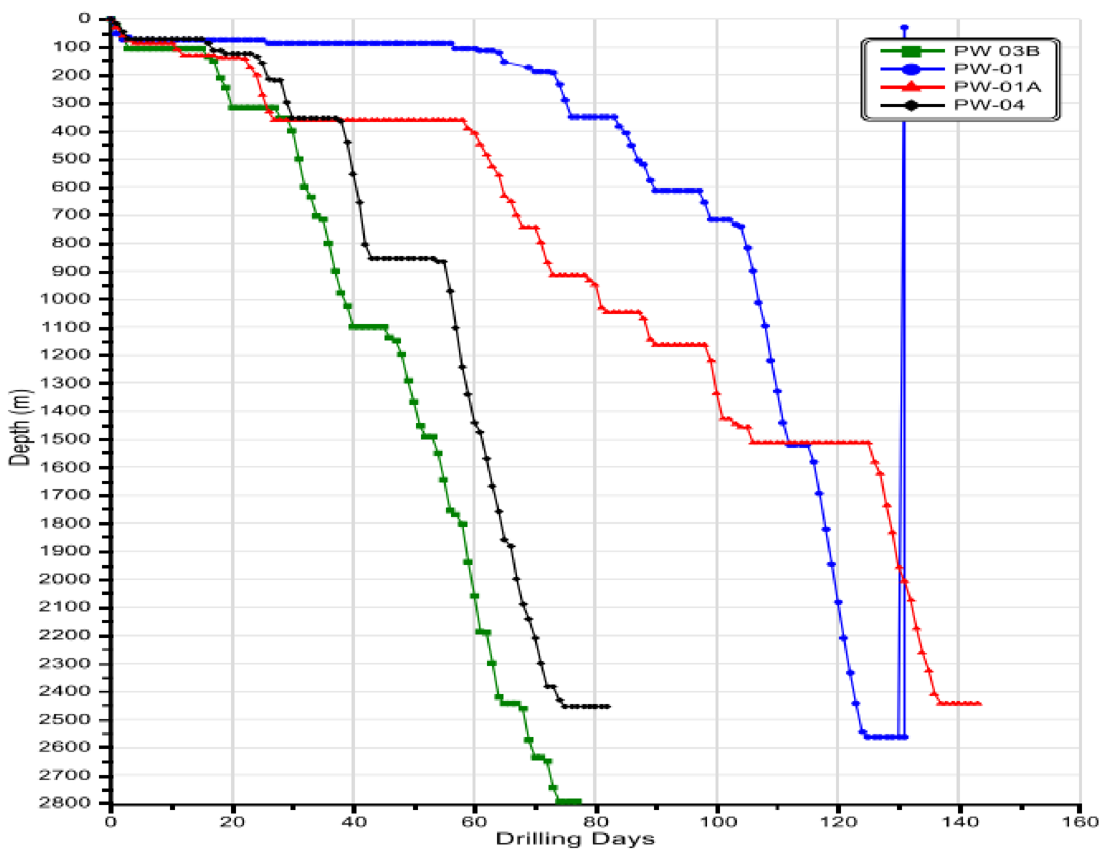


Figure 2: Drilling progress over time for wells in the Paka field (GDC, 2022).

2.2 Typical Well Design in Paka Geothermal Field

The Paka wells are designed to be drilled to a target measured depth of 3000 m. However, most of the wells drilled did not reach their target depth due to downhole drilling challenges of high torque and drag. Although formation factors may have resulted in these drilling challenges, insufficient hole cleaning and cuttings transportation is suspected to be one of the main causes. Table 1 shows a typical well design for wells drilled within the Paka geothermal field.

Table 1: Typical well design for Paka geothermal field.

Stage of well	Depth. m	Hole size, Inches	Casing size, Inches
Stage 1: Surface hole	0-100	26	20
Stage 2: Intermediate hole	100-350	17-1/2	13-3/8
Stage 3: Production hole	350-1200	12-1/4	9-5/8
Stage 4: Open hole	1200-3000	8-1/2	7 (Liner)

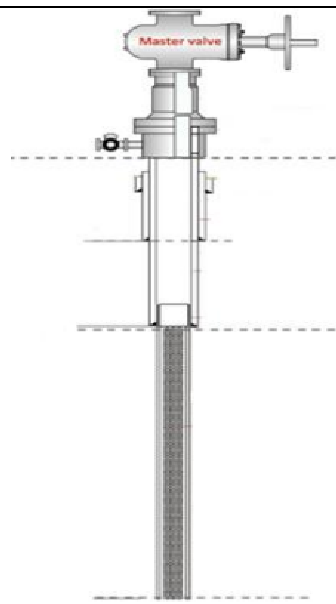
Hole Size	Drilled Depth	WELL PW-003B	Type & Size of casing	Casing shoe Depth
Class 900, 10 Inch master valve installed				
26″	107m		20″ Surface	102.9m
17½″	315m		13⅜″ Anchor	308.2m
Top of liner = 1024m				
12¼″	1099m		9⅝″ Production	1094m
8½″	2791m		7″ Liners	2743m

Figure 3: Profile of well PW-03B (GDC, 2022).

2.3 Well PW-03B

Well PW-03B is a directional well that was drilled to a depth of 2791 m with a maximum inclination angle of about 32°. The well was spudded on the 16th of September 2022 and was completed on the 2nd of December 2022 after 78 days. High torques and drag forces were experienced towards the completion depth. The well was terminated when those two parameters exceeded the design strength limit of the drill pipes. Figure 3 shows the well profile of PW-03B as drilled.

2.4 Drilling Fluids for Well PW-03B

The fluids used in drilling well PW-03B were water, bentonite mud, and foam that consists of water, air and detergent. The surface section was mainly drilled with bentonite mud and occasionally with water when total fluid losses were encountered. Whenever water was used to drill, Hi-Vis mud was used for sweeping the hole before connecting a new pipe. The intermediate and production sections of the well were drilled with foam. For the Paka field, the intermediate, production and open hole sections of the well are the ones that pose a big challenge. These sections are generally associated with frequent stuck pipes, and high torque and drag forces.

The intermediate section has the advantage of having the option of using Hi-Vis bentonite mud to address some of the challenges. There is also the option of performing cement plug jobs to seal off problematic sections. In contrast, the production and open hole sections encountered frequent stuck pipes, and high torques and drag forces. Thus the production and open hole sections are chosen as the sections that were modelled for cuttings transportation. This paper deals with the production section that has a 12-1/4″ hole diameter. The production section has a 12-1/4″ hole diameter and a casing diameter of 9-5/8″.

3. Numerical Simulation of Cuttings Transportation

3.1 TCT Simulator

The authors utilized the Transient-Cuttings-Transport (TCT) simulator developed by Naganawa and Nomura (2006). TCT has the ability to simulate cuttings behavior in directional wells as well as in extended reach wells that have complex trajectories. TCT implements mass and momentum conservation equations to describe multiphase flow of water/mud and solid rock cuttings particles within the annulus of a wellbore. It can also be used to describe additional flow of air within the well (Naganawa et al., 2017).

The well design data in Figure 3 was used in the simulation of cuttings transportation for well PW-03B. This paper covers cuttings transport modelling for the 12-1/4″ hole section from 308 m to 1099 m. The TCT simulator was used to describe the transport of fluids and cuttings up the well annulus during the drilling operations.

3.2 Data Collected from the Field.

To validate the simulations, drilling data was collected from well PW-03B as drilling was ongoing in the field. Cuttings from the well were collected and measured at the shale shakers for every drill pipe joint drilled. Other data collected include the rate of penetration (ROP), revolutions per minute (RPM) of the drill string, fluid flow rate and directional drilling data. Figure 4 shows cuttings collection and measurement at the shale shakers and the Geothermal Development Company (GDC) drilling rig.

3.3 Bottom Hole Cuttings Fill

After drilling each drill pipe, the well was circulated for between 30 and 45 minutes before adding a new drill pipe to drill ahead. Each time before drilling ahead, the bottom of the hole was sounded to check if there was any fill. Figure 5 shows the cuttings fill history. It was noted that fill was mainly encountered after stopping to conduct a deviation survey or after pulling out of the hole. In most cases, however, there was no fill.

Figure 4: Data collection at well site during drilling at Paka geothermal field. The two images on the left show the shale shakers where the drill cuttings were collected. The third image shows the weighing of collected cuttings, and the rightmost image shows the drilling rig.

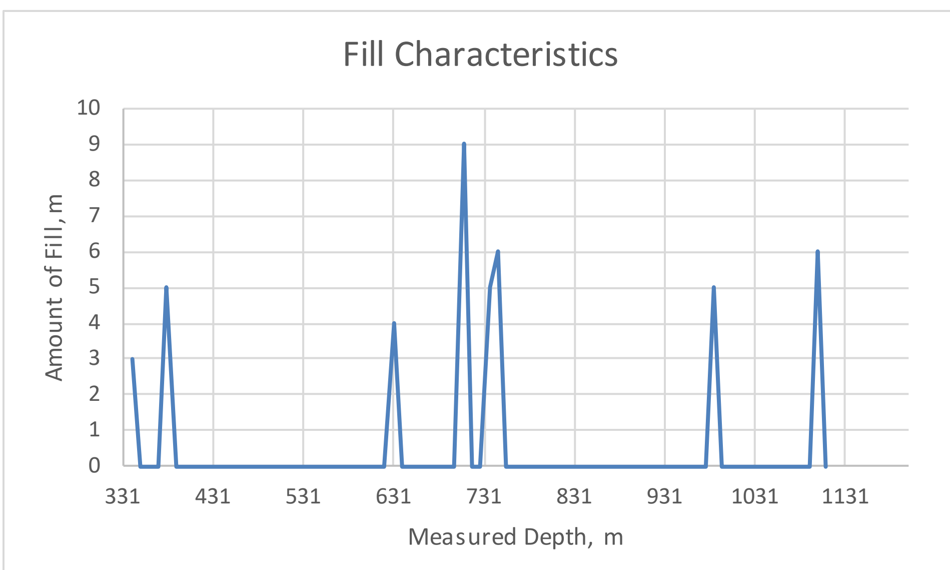


Figure 5: Fill characteristics for drilling of well PW-03B.

3.4 Rate of Penetration with Depth.

In selecting drilling bits, formation drillability plays an important role. Mostly, formations with high drillability will require soft formation bits and those with low drillability will require hard formation bits (Ford, 2004). Paka geothermal field has high drillability formations and with optimum parameters and a proper cuttings transportation setup, high penetration rates (ROPs) can be achieved. There are also quite a lot of instances of drill pipes getting stuck mostly due to insufficient hole cleaning. Figure 6 shows ROP along the trajectory of well PW-03B.

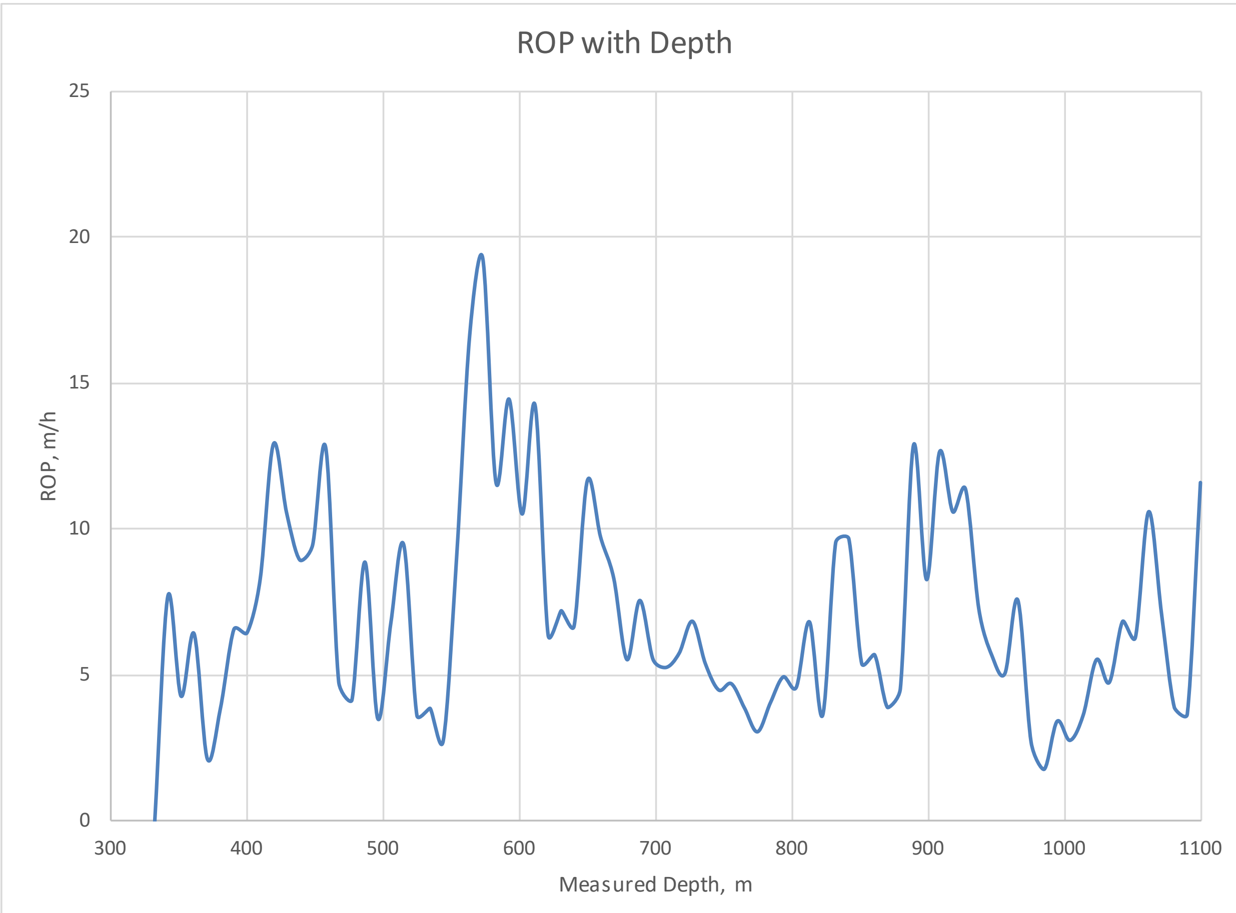


Figure 6: Rate of penetration (ROP) during drilling for well PW-03B.

4. Results of Cuttings Transport Simulation

In a bid to understand the behavior of cuttings movement within the wellbore annulus, several parameters were modelled. These are simulated returned cuttings, the cuttings bed height within the wellbore trajectory, cuttings concentration along the wellbore, equivalent circulating density (ECD) along the wellbore, and volumetric air rate along the wellbore.

4.1 Rheology of the Drilling Fluid Used in the Model

It is worth noting that Guo and Liu (2011) stated that that a foam drilling model from the work of Ozbayoglu et al. (2000) could be better characterized by using a power-law model for 0.7 and 0.8 foam qualities and Bingham plastic model give better fit for 0.9 foam quality. However, drilling fluid was assumed as a two-phase aerated water not a uniform foam because of a restriction of the simulation model. A Bingham plastic rheology is used for the liquid phase, and a two-phase friction factor between liquid and gas phases is also considered in the model.

4.2 Pumping Rates

Actual pumping rates of both air and water while drilling PW-03B were as follows. In drilling the well from 332m to 1100m, one compressor that delivered air at 1529 Nm^3/hr (normal cubic meters per hour) at 2.4 MPa was used. The rig had three triplex mud pumps with specifications as shown in Table 2.

Table 2: Mud pump properties.

Description	Quantity	Unit
Triplex Mud Pump	3	Number
Maximum Strokes Per Minute (SPM)	120	SPM
Liner Diameter	7	Inches
Stroke Length	305	mm
Maximum Pump Pressure	34.5	MPa
Pump Horsepower	1600	hp

Figure 7 shows the amount of water that was pumped at a given depth while drilling. This water was then mixed with air to form a uniform foam at the standpipe and pumped down the drill string.

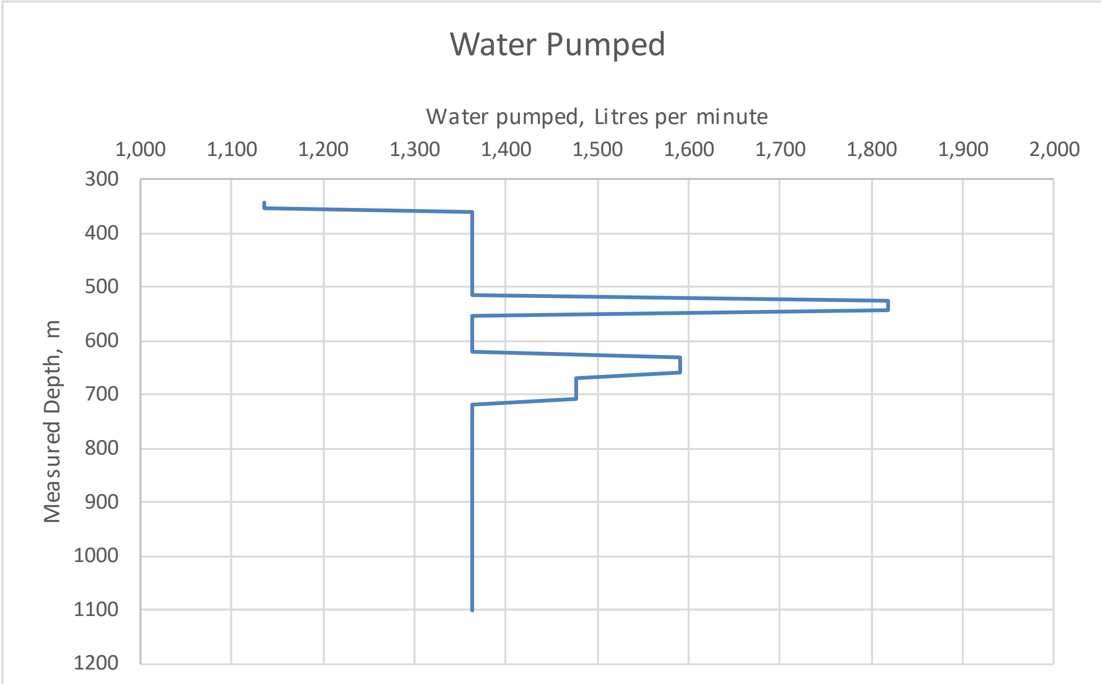


Figure 7: Water pumped while drilling PW-03B.

4.3 Properties of the Drilling Fluid Used in the Model

Table 3 shows the surface properties of the drilling fluid used in the model. As described before, the drilling fluid is dealt with as a two-phase liquid and air mixture in the model.

Table 3: Drilling fluid densities.

Fluid	Density	Unit
Water	1	g/cm^3
Air	1.3×10^{-3}	g/cm^3

4.4 General Well Profile and Cuttings Deposition in the Wellbore

It was noted that the wellbore was generally clear of cuttings as shown in Figures 8 and 9. The simulation results in Figures 8 and 9 showed that the wellbore had an insignificant amount of retained cuttings and the cuttings' bed height was small. This scenario may be attributed to long circulation times between drill pipe additions, which was factored in the simulation as periods drilling at zero ROP. A large cuttings bed height is usually a common phenomenon in highly inclined wells and extended reach wells (ERW) (Naganawa and Okatsu, 2008). Well PW-03B, on the other hand, is a moderately inclined well.

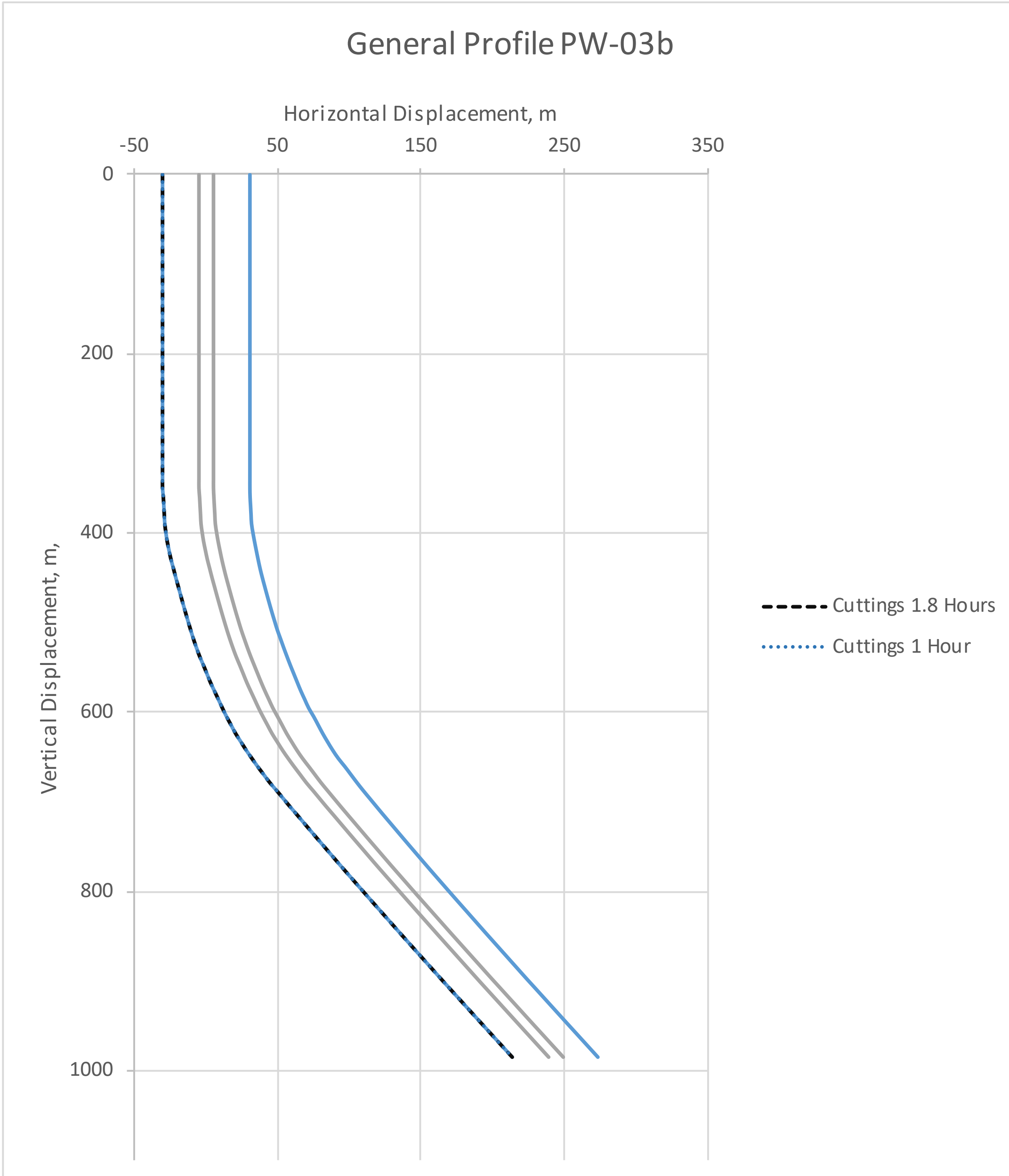


Figure 8: The well profile and the simulated cuttings deposits along the wellbore.

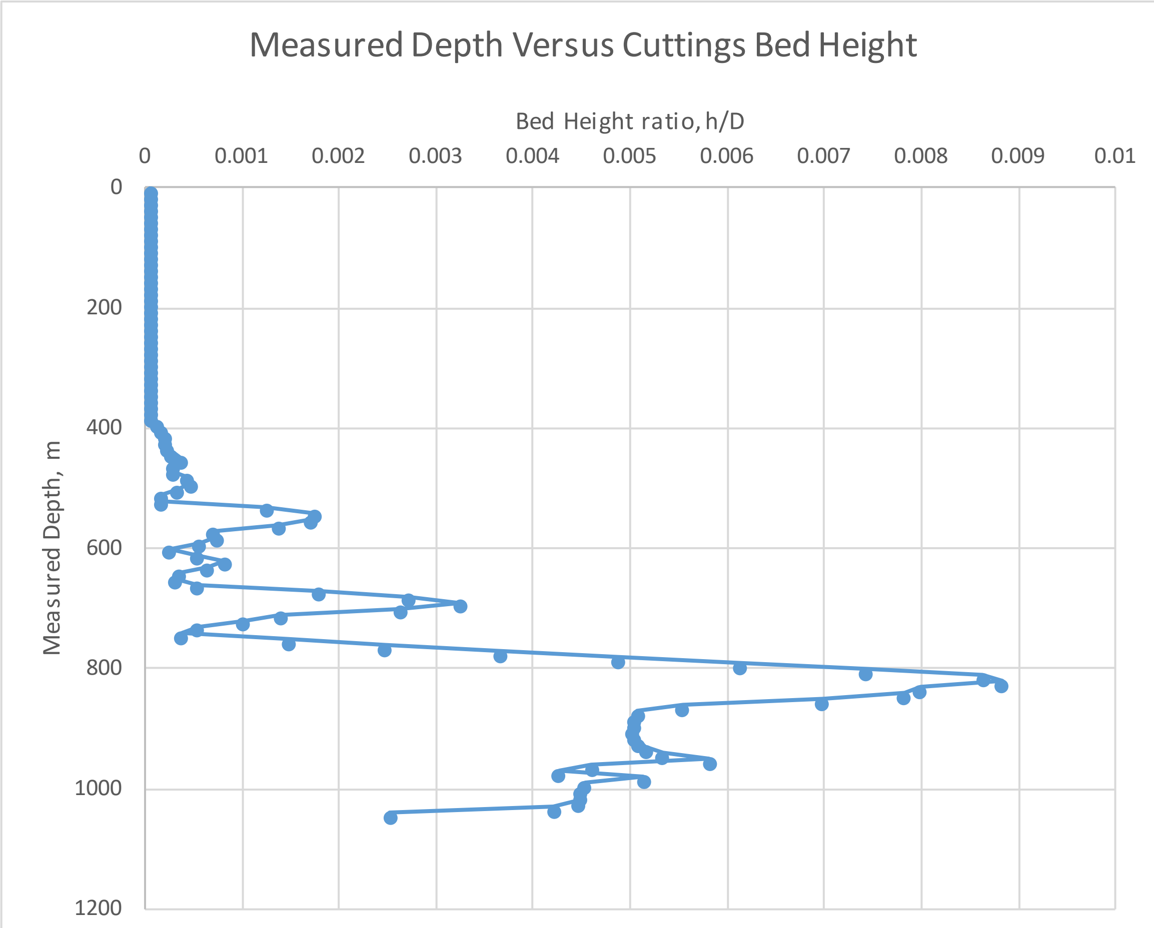


Figure 9: Simulated ratio of cuttings' bed height *h* to the hole diameter *D* along the wellbore.

4.5 Returned Cuttings

Cuttings from the wellbore were collected and measured in the field as drilling was going on. The model also simulated the returned cuttings. Figure 10 compares the measured cuttings returns in the field with the simulated cuttings returns and ideal cuttings returns for perfect, instantaneous cleaning. The ideal cumulative cuttings returns were calculated with the assumption that the wellbore was at gauge throughout the trajectory and that all cuttings are transported out of the hole instantaneously.

Surprisingly, the simulated cuttings results showed more cuttings transported to the surface than the ideal case. We expected the simulated returns to trend below the ideal scenario. Therefore, the simulations require further consideration. We note that the TCT simulator can be used to account for hole enlargement effects, whereby the cuttings returns will be higher than the case of a perfect gauge hole (e.g., due to caving in of unconsolidated sections). Therefore, it is possible that we mistakenly ran the simulations with an effective hole diameter larger than the gauge hole diameter.

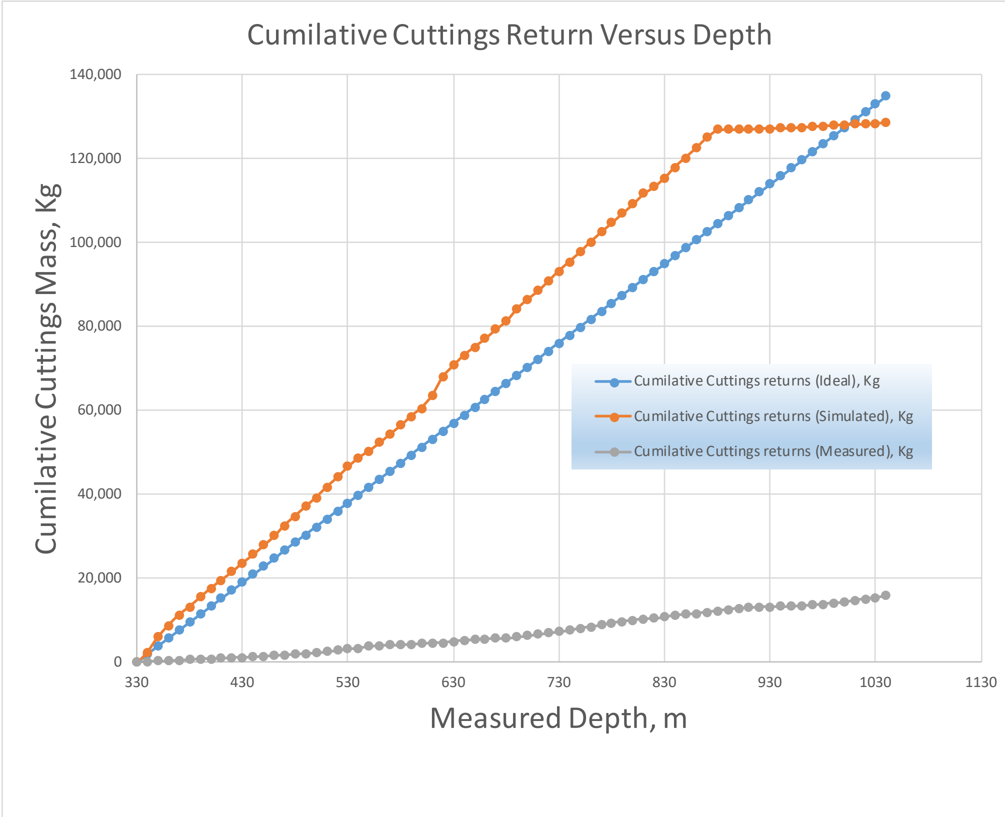


Figure 10: The cumulative cuttings characteristics.

Note that the data from the field showed that only a small fraction of the generated cuttings were returned to the surface (Figure 10). The lower than expected cuttings returns to the surface can in part be explained by the fact that not all the surface cuttings were collected and measured. The cuttings returned at the surface were generally not measured for the hole cleaning periods in between pipe additions. Nevertheless, we expect that the missed drill cuttings were relatively insignificant. Based on that assumption, these results indicate that a considerable amount of cuttings were lost in the field to fractured or permeable formations. In this ongoing research, we aim to calibrate the TCT simulations with the field conditions to get a better understanding of the hole-cleaning behavior. We will consider including fluid losses in the simulations to account for the apparent loss of circulation seen in the field.

4.6 Velocity Characteristics

It's generally accepted that a minimum annular solid velocity of about 0.25 m/s is satisfactory for cuttings transport for a typical drilling fluid (Bourgoyne et al., 1991). From the simulation, this was achieved as shown in Figure 11. The velocity of the cuttings and the fluid phases is as shown in Figure 11. As shown, the minimum liquid phase velocity was above 0.4 m/s.

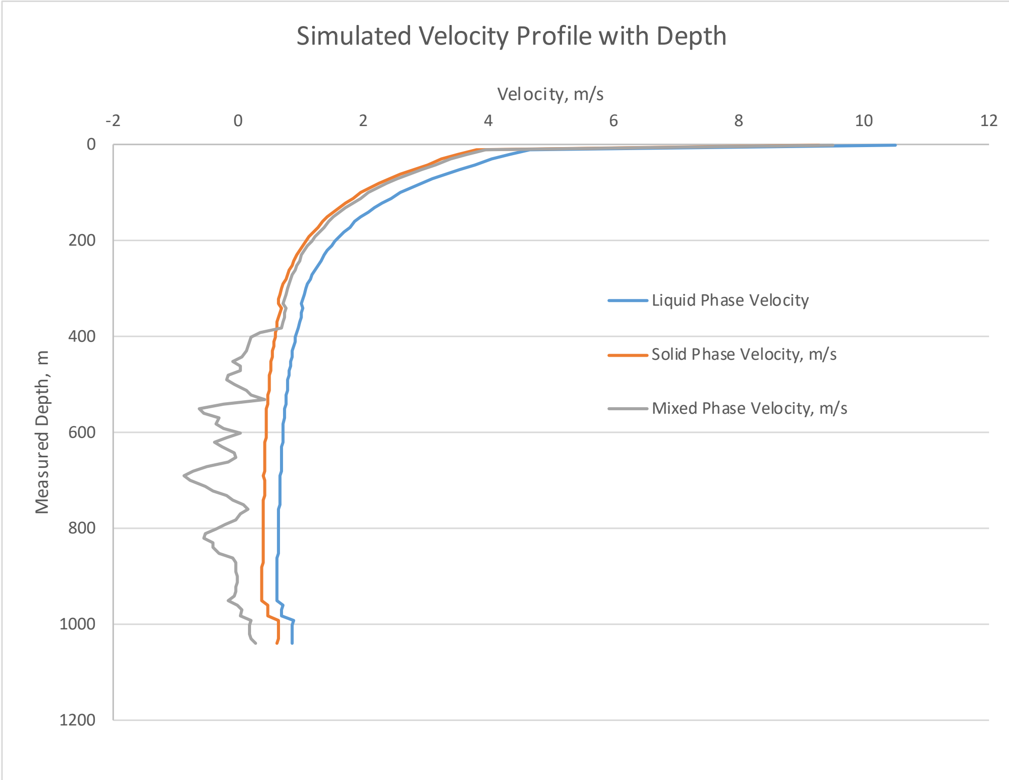


Figure 11: Velocity profiles of the fluid phases within the annulus.

4.7 Equivalent Circulating Density (ECD)

Depending on the depth, the column pressure of a drilling fluid may fracture the formation and induce fluid losses during drilling. A safe ECD must be maintained if loss of circulation is to be avoided. Values of ECD of about 1550 kg/m^3 may fracture some formations at quite shallow depths of less than 2000 m (Zhang and Yin, 2017). The ECD for the simulation was quite low as seen in Figure 12 because of the aerated water used as the drilling fluid.

5. Discussion and Recommendations

A look at Figures 2, 6, 8 and 9 suggested that it is possible to attain higher ROPs and to reduce the total drilling time significantly. Figures 2 and 6 from data collected at the rig show that a high ROP of up to 20 m/hr could be feasible. More studies on the combination of parameters that will achieve these high ROPs will be simulated and then subsequently tested at the field.

The simulation results in Figures 8 and 9 indicate that there is very little cuttings concentration within the wellbore annulus. This directly implies that there is room for generating more cuttings at higher ROPs without risking the safety of the well. This will be considered in the next stage of this simulation study.

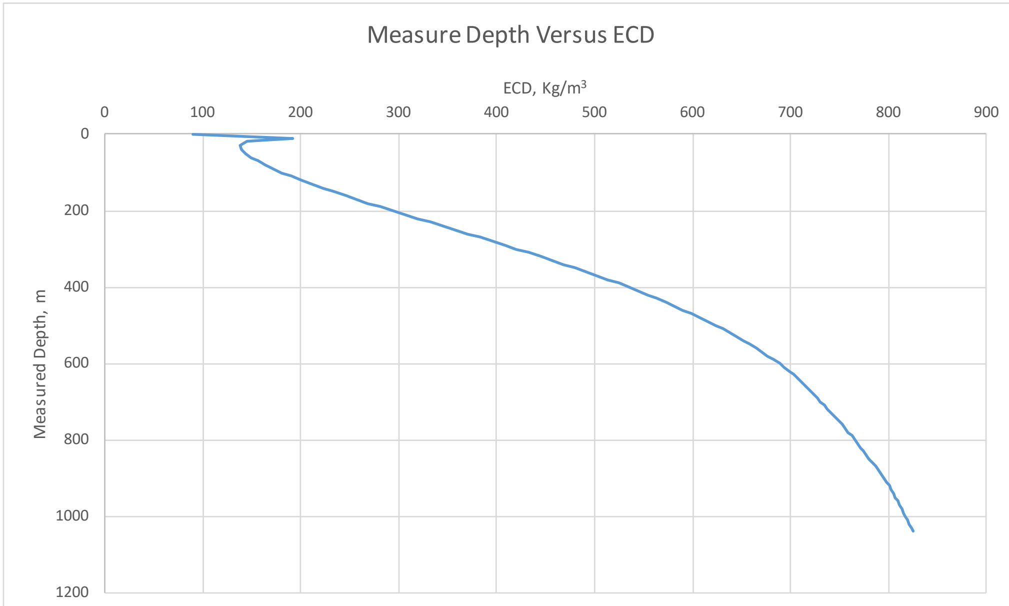


Figure 12: Variation of equivalent circulating density (ECD) with depth.

Figure 11 shows the velocities of the phases during cuttings transportation. The velocities appear low at the deeper sections of the well. This may explain the reason why high torque and drag forces are experienced at the deeper sections of the well. There will be a need to simulate parameters that will result in higher annular velocities within deeper sections of the well. This will promote faster evacuation of cuttings generated to create room for drilling ahead, and also to reduce the high torque and drag that is experienced. It is recommended to run simulations and develop an operation manual for parameters that will lead to improved drilling performance. This is a research direction and work that will be considered in the future.

6. Conclusion

The simulation results showed that most of the parameters used in drilling well PW-03B were within the safe limit and there is room for optimizing the parameters such as the ROP if the cuttings transportation system is optimized. This paper is part of ongoing research to optimize the cuttings transportation in order to reduce the drilling time and thus reduce the cost of drilling. The next phase of the research will attempt to come up with precise drilling fluid flow rates and recommended ROPs to realize reduced drilling times.

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