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MODELLING AND OPTIMIZATION OF GEOTHERMAL DRILLING PARAMETERS - A CASE STUDY OF WELL MW-17 IN MENENGAI, KENYA

Report 6
December 2014

UNU GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2014
Number 6

MODELLING AND OPTIMIZATION OF GEOTHERMAL DRILLING PARAMETERS - A CASE STUDY OF WELL MW-17 IN MENENGAI, KENYA

MSc thesis
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United Nations University
Geothermal Training Programme
Reykjavík, Iceland
Published in December 2014

ISBN 978-9979-68-344-5
ISSN 1670-7427

This MSc thesis has also been published in November 2014 by the
School of Engineering and Natural Sciences,
Faculty of Industrial Engineering, Mechanical Engineering and Computer Science
University of Iceland

INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) has operated in Iceland since 1979 with six month annual courses for professionals from developing countries. The aim is to assist developing countries with significant geothermal potential to build up groups of specialists that cover most aspects of geothermal exploration and development. During 1979-2014, 583 scientists and engineers from 58 developing countries have completed the six month courses, or similar. They have come from Asia (37%), Africa (36%), Central America (15%), Europe (11%), and Oceania (1%) There is a steady flow of requests from all over the world for the six-month training and we can only meet a portion of the requests. Most of the trainees are awarded UNU Fellowships financed by the Government of Iceland.

Candidates for the six-month specialized training must have at least a BSc degree and a minimum of one year practical experience in geothermal work in their home countries prior to the training. Many of our trainees have already completed their MSc or PhD degrees when they come to Iceland, but several excellent students who have only BSc degrees have made requests to come again to Iceland for a higher academic degree. From 1999 UNU Fellows have also been given the chance to continue their studies and study for MSc degrees in geothermal science or engineering in co-operation with the University of Iceland. An agreement to this effect was signed with the University of Iceland. The six-month studies at the UNU Geothermal Training Programme form a part of the graduate programme.

It is a pleasure to introduce the 40th UNU Fellow to complete the MSc studies at the University of Iceland under the co-operation agreement. Thomas Ong'au Miyora, BSc in Mechanical Engineering, from Geothermal Development Company - GDC, Kenya, completed the six-month specialized training in Reservoir Engineering at the UNU Geothermal Training Programme in October 2010. His research report was entitled: *Controlled directional drilling in Kenya and Iceland.* After two years of geothermal research work in Kenya, he came back to Iceland for MSc studies at Faculty of Industrial Engineering, Mechanical Engineering and Computer Science in February 2013. In November 2014, he defended his MSc thesis presented here, entitled: *Modelling and optimization of geothermal drilling parameters - A case study of well MW-17 in Menengai Kenya.* His studies in Iceland were financed by the Government of Iceland through a UNU-GTP Fellowship from the UNU Geothermal Training Programme. We congratulate him on his achievements and wish him all the best for the future. We thank the Faculty of Industrial Engineering, Mechanical Engineering and Computer Science at the School of Engineering and Natural Sciences of the University of Iceland for the cooperation, and his supervisors for the dedication.

Finally, I would like to mention that Thomas' MSc thesis with the figures in colour is available for downloading on our website *www.unugtp.is*, under publications.

With warmest greetings from Iceland,

Ludvik S. Georgsson, director
United Nations University
Geothermal Training Programme

ACKNOWLEDGEMENTS

I wish to thank God for enabling and sustaining me throughout my study period at the University of Iceland.

I am indebted to the Icelandic government, United Nations University GTP and Geothermal Development Company Limited who financially made the study possible.

I wish to specially thank the UNU-GTP staff: Director, Mr. Lúdvík S. Georgsson, Ingimar G Haraldsson, Þórhildur Ísberg, Maria S. Gudjonsdottir, Málfríður Ómarsdóttir and Markús A. G Wilde who supported me and made my stay comfortable in Iceland. I also wish to thank the Masters and PhD fellows at UNUGTP for their support and encouragement.

I wish to thank in a special way my supervisors Professor Magnús Þór Jónsson and Sverrir Þórhallsson who patiently guided and helped me in this research.

I wish to thank L. Okwiri, I. Makuk, A. Khaemba, M. Kamau and W. Kivure who took their time to get me the drilling data and other important information.

I thank my parent, brothers and sisters for their encouragement. I also wish to thank my friend O.J who gave me moral support during my study period.

Finally special gratitude to my family, my dear wife Evah, my daughters Monicah and Jedidah and son Peter who had to endure my absence and moreover gave me the moral support to endure the separation while undertaking the study.

ABSTRACT

Several factors come into play when a drill bit is crushing the rock at the bottom of the hole. To effectively drill geothermal wells, these factors must be carefully considered and combined in an optimum manner. The characteristic of geothermal formations is such that it is composed of different layers of rocks alternating from the surface to the final depth. Some rocks are highly temperature altered while others are highly fractured and unconsolidated. A careful approach has to be devised while drilling through the different sections to avoid problems which lead to delays in drilling. At the same time drilling parameters have to be applied according to the rock types in such a way that the well is drilled in the shortest time possible and in the most cost effective manner. The following factors have been mathematically modelled by Multiple Linear Regression and shown how they affect the overall drilling rate: Formation strength, depth, formation compaction, pressure differential, bit diameter and weight on bit (WOB), bit rotation (RPM), and bit hydraulics. This modelling approach has been adapted for geothermal drilling from the oil and gas drilling as first applied by Bourgoyne and Young. Optimization of WOB and RPM showed most of these parameters are in some cases applied too low and in others too high. Data captured while drilling of well MW-17 in Menengai geothermal field was used in making the drilling model. A combination of Excel and MatLab was used in the data analysis.

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

1. INTRODUCTION

Geothermal energy is one of the renewable energy sources with a wide range of applications. This energy is accessed from the earth's interior to supply heat for direct use and to generate electricity. Climate change is not expected to have a major impact on the effectiveness of geothermal utilization, but the widespread use of geothermal energy could play a significant role in mitigating climate change. Geothermal resources are not dependant on climate conditions. The impact that climate change may have on the geothermal utilization is change of rainfall patterns which in turn affect recharge of the geothermal reservoirs. This can be mitigated by re-injection. Since geothermal resources are underground, exploration methods including geological, geochemical and geophysical have been applied to locate and assess them. Drilling of exploration wells helps confirm the properties of the resource hence minimizing risk. Geothermal wells are drilled over a range of depths down to 5km using methods similar to those used for oil and gas (IPCC, 2012). Drilling and completing new wells is costly and those costs account for 30 to 70% of the initial capital expenses for oil and gas field developments (Teodoriu et al., 2011), and in geothermal drilling, it accounts for approximately 54% of the total development (Hole, 2013).

There are more than fourteen high temperature geothermal prospects in Kenya with an estimated potential of more than 15,000 MWe (GDC, 2010). Menengai is one of the high temperature geothermal fields found within the Kenya Rift Valley. The Kenya rift is part of the Eastern arm of the East African Rift System. The litho-stratigraphic successions in the Menengai geothermal field are predominantly trachytes. Other rock types found include pyroclastics, tuff, syenite and basalt. (Kipchumba, 2013). Exploration Drilling in Menengai geothermal field started in 2011 with drilling of well MW-1. By November 2014 Over 30 geothermal wells had drilled in Menengai field. Drilling is ongoing with 4 large rigs and 3 more are to be commissioned at the field.

The objective of this thesis is to make a mathematical model of the rate of penetration (ROP) considering all the parameters that make the bit to drill through the rocks in the formation. After modelling of the drilling process, optimization of the controllable parameters will be done. Data for well MW-17 from Menengai field in Kenya is used for this case study. The well was drilled in 2013 to a depth of 2218 m in 121 days. MatLab and Excel is used in the data analysis and modelling. Excel spreadsheet was used in the initial processing of the data to remove noisy data, and in the calculations of equivalent circulation density and pore pressure gradient. It was also used in the calculations of modelled rate of penetration using regressor constants ('a_is') from MatLab, do sensitivity analysis and optimization. MatLab was used in executing the multiple linear regression to calculate the regressor constants.

The modelling approach applied in this thesis was adapted from the oil and gas drilling. The formation type in the oil fields is more homogeneous than in geothermal fields. The formation type is mostly shale and sandstone in the entire depth (Eren, 2010). When applying regression to determine the regressors for predicting the rate of penetration in oil wells, it is possible to use the same parameters for the entire well because of the homogeneous formation. In his paper, Bourgoyne et al., 1974 and Eren, 2010 used a single parameter of threshold wait on bit for the entire well depth in their modelling of rate of penetration. Bourgoyne et al., 1991 used a threshold value of zero for some wells in modelling for rate of penetration implying that the formations were soft. Unlike Petroleum fields, the formations of geothermal fields vary from the surface to the bottom of the well being drilled. The stratigraphy of well MW-17 used in this modelling shows alternating layers of different types of rocks from the surface to the bottom of the well (Section 4.4).

To use the method of modelling for rate of penetration used in the oil and gas industry, portions of the well with the same formation types have to be modelled separately. This was done by dividing the well into sections according to the rock types. By dividing the well into sections with the same type of formations, and then modelling the sections independently, the process of applying the Bourgoyne and Young model in geothermal wells is possible.

1.1 Research outline

Drilling of wells in Menengai geothermal field in Kenya takes longer to complete than usual. This is because of challenges encountered when drilling through different sections of the well. The surface section is characterised by hard and abrasive formations which cause excessive vibrations of the drillstring when high rotations and weight on bit are applied. The Intermediate hole is characterised by hard formations and loss of circulation. The production hole has good drillability but frequent loss of circulation and the drillstring getting stuck are common. One possible solution to these challenges is to apply the right drilling parameters. The parameters such as Weight on bit (WOB), Rotations per minute (RPM) and pumping rate are easily controlled by the operator and if rightly applied, they can improve the drilling performance greatly.

The objective of this thesis is to attempt to determine the best controllable drilling parameters to apply in each section of the well when drilling. The first step will be to model the drilling process and get the output as the rate of penetration. The next step will be to optimize the rate of penetration by optimizing the input variables to the model.

This is will be done by first analysing the data for well MW-17 on the parameters used. The data are then processed and used to model the rate of penetration by applying Bourgoyne and Young's method of multiple linear regressions. The inputs to this model are Depth, rate of penetration (ROP), Rotations per minute, bit diameter, weight on bit, threshold weight on bit, Equivalent circulating density at bottom of the hole, pore pressure gradient, Reynolds number function, the bit teeth wear, the density of the circulating fluid and the pumping rate.

The process of modelling will require determining all the input variables needed into the model. Most of these input variables to the model are captured by the data acquisition systems at the rig such as the depth, the bit rotations per minute, the weight on bit, and the pumping rate. Some of the variables such as Equivalent circulating density, the pore pressure gradient and the Reynold's number function require mathematical calculations using the data that was captured. Finally, there are those variables that require tests to be done on the formation while drilling such as threshold weight on bit for each formation type. These tests were not done when drilling well MW-17 and therefore, the value of threshold weight on bit for the different formations will be determined from past research work on similar formations from other fields and used in this modelling.

When all the input variables have been determined, modelling will be done by multiple linear regression and the regressor constants for each section determined. These constants will then be used to model the rate of penetration.

1.2 Background research

A lot of research on modelling and optimization of drilling parameters has been done. This section looks at past research on optimization of drilling. Most of the drilling models developed use different models separately for the different drilling parameters. For instance one model is developed for optimizing the weight on bit and the rotary speed, a different model is used for optimizing bit hydraulics and yet a different model for formation drillability. The following is the progression of modelling of optimization in drilling from the 1950s when research on optimization of drilling parameters started.

John Speer in 1958 developed five relationships between weight on bit, rotary speed, hydraulic horsepower, and effect of weight on bit (WOB) on formation drillability and how the optimum rotary speed is related to the weight on bit. He combined the five relationships into a chart for determining optimum drilling techniques from a minimum of field test data. Speer Identified five factors that affect bit performance as: Weight on bit, rotary speed, hydraulic horsepower, type of bit, and properties of the circulating medium (Speer, 1958).

Regression analysis of past drilling data to obtain constants in a drilling rate equation was proposed by Graham and Muench in 1959. They derived empirical mathematical expressions for bit life expectancy, drilling rate as a function of depth, weight on bit and rotary speed. They then applied regression on past drilling data to determine drilling constants that enabled them to determine optimum weight on bit and rotary speed combinations (Bourgoyne et al., 1974; Eren, 2010).

Maurer in 1962 developed a drilling-rate formula for roller corn bits derived from the mechanisms of creating 'craters' on the rock. The formula was based on the condition that there is perfect cleaning of the hole where all rock cuttings are removed from below the drill bit. Maurer stated his formula as "the drilling rate is directly proportional to the rotary speed and to the bit weight squared, and inversely proportional to the bit diameter squared and to the rock strength squared". This relationship was incorporated into Bourgoyne's drilling parameter for formation strength (Maurer, 1962).

Galle and Woods in 1963 modelled rate of penetration based on the best constant weight and rotary speed for the lowest drilling cost for roller cone bits. They applied their model in several field tests which showed reduction in drilling cost. In their model they showed procedures for, the best combination of constant weight and rotary speed, the best constant weight for any given rotary speed and the best constant rotary speed for any given weight, (Galle et al., 1963).

Grant Bingham in 1965 did compression tests on rocks in an attempt to relate drilling rate to the properties of the rock. He found out that the threshold force required to initiate drilling in a given rock at atmospheric pressure could be correlated to the shear strength of the rock. He did experiments with various rocks to determine their threshold strength. He presented his results in a graph of critical shearing stress against the square root of apparent intercepts (threshold strength) for these rocks and the plot could be approximated by a straight line (Section 4.3.3) (Bingham, 1965).

The effect of hydraulics was modelled by Eckel in 1966-1968 in his studies on microbits on rocks. He showed that in one rock under conditions of fixed bit weight, rotary speed, and differential pressure, drilling rate could be expressed as a simple power function of mud flow properties, and power function of mud flow properties and hydraulic parameters. When the weight on bit, rotary speed and differential pressures were varied, the changes in these parameters caused changes in the drilling rate but not in the effect of fluid properties and hydraulics hence drilling rate can be expressed as an exponential function of a pseudo Reynolds number involving flow rate, nozzle diameter, fluid viscosity and density of the mud (Eckel, 1968).

Young F.S developed a method of determining optimum weight and rotary speed at the well site with a computerized drilling control system. He developed equations relating drilling rate as a function of weight on bit and bit teeth height, bit wearing rate as a function of rotary speed, an equation about bit teeth wear rate and an equation about drilling cost. He then optimized the weight on bit and the rotary speed to get the best solution (Eren, 2010).

Reed in 1971 developed a variable weight-speed model which was solved using Monte Carlo scheme by minimising cost per foot drilling. It was reported that optimal drilling was achievable not only by optimising on weight on bit and rotary speed, but also for the hydraulics, bit selection, well design, mud treatment and solids separation (Eren, 2010).

In 1974, Bourgoyne and Young developed an optimal drilling model using multiple regression approach. They considered most of the factors that affect rate of penetration and combined them in one mathematical equation. They then applied multiple regression approach to find the regressor constants that they used to predict the rate of penetration. Their model combined findings from many models developed previously into one model by using synthesis of previous field data (Bourgoyne et al., 1974).

Wilson and Bentsen evaluated various procedures for optimizing drilling that involved weight on bit and rotary speed. They developed three methods: Point optimization that minimizes cost per foot during a bit run; Interval optimization that minimizes the cost of a selected interval; Multi-interval optimization that minimizes cost over a series of intervals. The authors intended to have a model that will be the basis for good drilling procedures and cost saving. (Eren, 2010).

In 1985, Al-Betairi presented a case study of the Arabian Gulf area. They applied the model by Bourgoyne and Young which they validated with Statistical Analysis System. They observed that for particular set of coefficients, the model became sensitive. Severity of multicollinearity effect on each parameter was observed to be inversely proportional to the influence of that parameter on the rate of penetration. The accuracy of estimating the optimum weight on bit and rotary speed suffered due to presence of multicollinearity in their model (Eren, 2010).

Warren modelled the rate of penetration using roller cone bits and concluded that the rate of penetration is controlled by either the cuttings generation process or cuttings removal process. Warren suggested that good rate of penetration models must include cuttings removal because they affect the rate of penetration. The model was used to show that the reduction in penetration rate at high borehole pressure was as a result of both cratering effects and global cleaning effects. He further concluded that increased hydraulics will increase the rate of penetration when it is limited by global cleaning effects (Warren, 1987).

Maidla and Shiniti used data from five wells located in offshore Alagoas, Brazil to test two models. He showed that the rate of penetration of the fifth well could be predicted using coefficients calculated from the four previous wells. He tested Bourgoyne and Young model and the model they developed using dimensional analysis (Maidla et al., 1985).

In their model entitled Optimization of multiple bit runs, Barragan and Santos researched on a model that is based on multiple bit runs using a heuristic approach to seek the optimum conditions by using Monte Carlo simulation and specially developed numerical algorithms. The output of the model yields the operating conditions for each individual bit run so that the overall costs are minimized for the entire well phase being drilled. The model doesn't depend on any model but has been tested with several models such as Bourgoyne and Young´s, Warren´s and others. This model results in extensive cost saving (Barragan et al., 1997).

Simmons modelled real time drilling optimization by coupling several parameters in order to achieve drilling efficiency. His model used previous offset data to predict with reasonable reliability the parameters and the magnitudes required for drilling optimization for the well being planned. His model could also be modified on site according to the prevailing conditions during drilling to get the best parameters in order to achieve optimum performance (Simmons et al., 1986).

Eren in 2010 developed a real time optimization model using Bourgoyne and Young's model that could pipe data as it is generated at the field, through the World Wide Web to a central computer which continuously calculates the developed model parameters by multiple regression and inform the field team. The field engineer will transmit the current drilling parameters back to the central computer and a new model parameters and optimum drilling parameters are determined by including recently received information. This is done on real time (Eren, 2010).

1.3 Result of background research

A lot of research work has been done in the area of modelling and optimization, most of them aimed at reducing cost. The early models concentrated on modelling a few parameters that affect drilling rate while assuming or holding the other factors constant. Later a comprehensive and detailed modelling involving most of the parameters that affect rate of penetration were included. Currently optimization models have been developed that are capable of achieving real-time-optimization of the parameters affecting rate of penetration. The data from the data acquisition systems is piped via the World Wide Web to a central computer, the data is optimized and the optimum parameters relayed back to the field on real time basis for application. According to Eren, 2010, Bourgoyne and Young's model is the most important drilling optimization method since it is based on statistical synthesis of the past drilling parameters.

Most of the models have been developed for use in the oil fields where the formation is mainly homogeneous. This study has adapted the Burgoyne and Young's model into geothermal drilling modelling and optimization. Data from one well (MW-17 in Menengai Kenya) is used in the case study of this model. In order to mimic the homogeneous formation in the oil fields, the well is modelled in sections with uniform formation down the hole. A total of twenty one sections from the well were modelled.

2. OVERVIEW OF THE DRILLING PROCESS

Drilling is the process of making a hole either vertically or directionally into the earth to tap the resource stored in reservoirs such as oil, gas, water, heat, steam and others. The drilling operation is carried out by a rig which has several operating systems.

According to Azar, 2007, drilling for these resources require two major constituents: skilled manpower and hardware systems. In addition to these, hardware and consumable materials such as casings, cement, mud, water and others are needed in the making of the holes. The manpower encompasses a drilling engineering group and a rig operations group. The drilling engineers provide support for optimum drilling operations in selection of the type of rig, designing the mud program, casing and cementing programs, the hydraulic program, the drill bit program, the drill string program, and the well control program. Rig operations group handle the daily operations and the personnel include the tool pusher and the drilling crew such as the derrick and motor personnel, the drillers, the rig floor men, the roustabout, etc. The hardware systems from the rig include:

- A power generation system;
- A hoisting system;
- A drilling fluid circulating system;
- A rotary system;
- Well blowout control system;
- A drilling data acquisition and monitoring system.

2.1 Drilling personnel

Drilling a well requires many different skills. Depending on the nature of management of the drilling project that is in place, the personnel that work at the drilling rig will differ as per the number of companies involved with the project. The company who manages the drilling and/or production operations is known as the operator. The drilling contractor is the company employed to actually drill the well and it owns the rig and employs and trains the personnel that operate the rig. In the course of drilling the well, specialised skills and equipment such as for directional drilling, cementing, logging, surveying, fishing etc. will be required and these are commonly provided by service companies but sometimes in-house by the drilling contractor. The service companies contract their tools and personnel to the operator generally on day rate basis (Ford, 2004).

The types of contracts for drilling services range from day-rate contracts to turnkey contracts. In Iceland, geothermal drilling operations are executed under contract structures which are predominantly based on a metre-rate and are referred to as being integrated as it encompasses all services and materials. In New Zealand, Kenyan and Indonesian geothermal drilling operations, the contracts are predominantly day-rate (unit time rate contracts) (Hole, 2006). The most common type of contract is day-rate contract. The drilling contractor follows a detailed Drilling Program prepared by the operator and the drilling contractor provides the drilling rig and personnel to drill the well. The drilling contractor is paid a fixed sum of money for each day spent in drilling the well. All consumables, transport and services are provided by the operator (Ford, 2004).

In the turnkey contract, the drilling contractor comes up with the drilling program, provides transport, services and consumables and charges the operator a fixed sum of money for the whole project. The role of the operator is to specify the drilling targets, the evaluation procedures and to establish the quality controls for the final well (Ford, 2004).

The operator will generally have a representative at the rig called a "company man" who ensures that drilling is carried out according to the drilling program, makes decisions affecting the well drilling and organizes supplies of consumables to the rig. The company man liaises with the drilling superintendent who is based in the operator's office. The operator may also have personnel such as the drilling engineer and geologist at the rig.

The drilling contractor has a toolpusher at the rig who is in overall charge of the rig and co-ordinates the drilling crew to ensure that drilling progresses is as planned. The drilling crew includes: the driller, the derrickman, the floormen/roughnecks, mechanic, electrician, crane operator, and roustabouts.

The service company personnel are at the rig when their services are required. Such personnel include cementing engineers, directional drilling engineer, mud engineer, etc. Figure 1 (Adapted from Ford, 2004) shows the personnel involved in drilling a well.

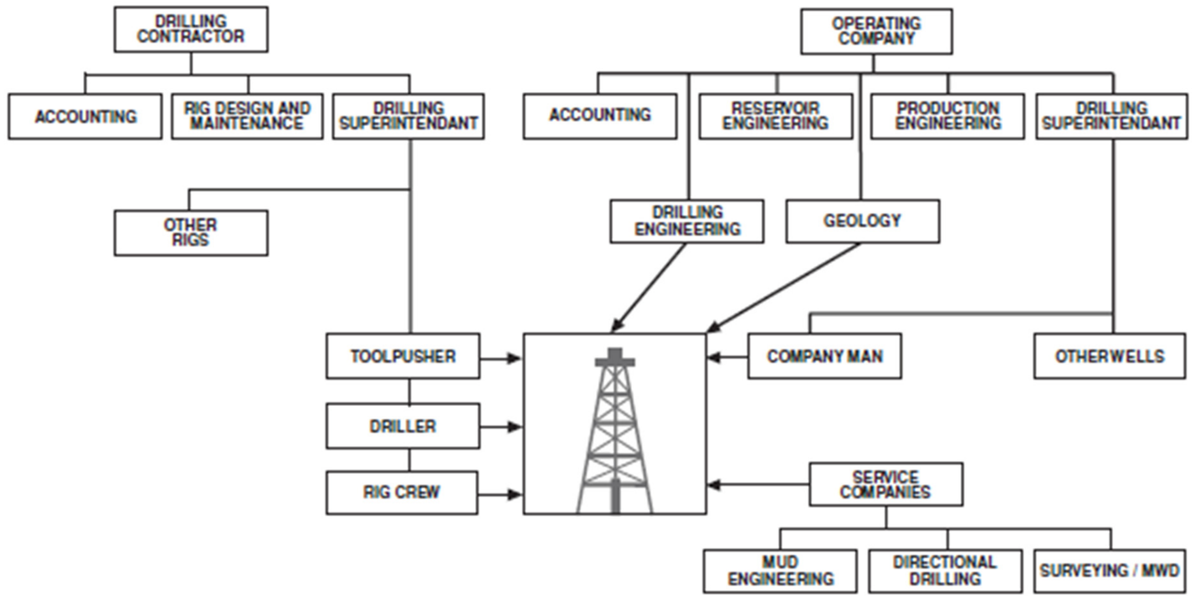

FIGURE 1: Personnel involved in drilling

2.2 Hardware drilling systems for a rotary rig

Before drilling commences, the type of a rig to be used has to be selected. The main objective of rig selection is to choose from the available rigs the one that will closely meet the criterion for drilling a hole at the lowest overall cost. The selection process is directly related to evaluation of the rig systems of the available rigs (Azar, 2007)

2.2.1 Power generating system

The power of rotary drilling rigs is usually generated by diesel or gas driven internal combustion engines. This is because most drilling is done in remote locations where grid power is not available. The power that is generated is transmitted to various rig systems by means of mechanical drives such as chains, compounds, torque converters and V-belts or by means of electrical drives using motors. The mechanical transmission systems were used for older rigs (Azar, 2007; Ford, 2004). The electric drive systems of most modern rigs consist of DC/DC systems AC/SCR systems and AC/VFD systems. Each system consists of engine/generator sets, control systems and electric motors (IADC, 2000).

The DC/DC system requires that one or more DC generators be specifically assigned to a DC motor to meet the desired load requirement for the equipment at a controllable speed. The DC motors are used on mud pumps, drawworks and rotary table. In the DC/DC systems we also have AC generators that operate auxiliary functions that require alternating current (Azar, 2007). The DC/DC systems are generally arranged so that each motor can receive power from two or more generator sets to provide backups in case of failure of any engine (IADC, 2000). The disadvantage of DC/DC system is that the specific assignment of generator sets leads to operating with more engine capacity than the total rig power would justify (Azar, 2007)

Most modern rigs have an AC/SCR system that includes multiple AC generator sets, AC to DC conversion systems and controls connected to DC motors (IADC, 2007). The advantage of AC/SCR system is that all of the generated AC power is fed to a common bus and converted to DC only as needed (Azar, 2007).

2.2.2 Hoisting system

The function of the hoisting system is to lower and raise equipment into and out of the well. The hoisting system consists of a powerful pulley system. The components of the hoisting system are discussed below:

- Drawworks: It consists of a large revolving drum round which a drilling line is spooled. The other components of the drawworks include the brakes, the transmission and the cathead. The driller controls the drawworks with a clutch, gearing system and the friction brake and electric brake.
- Blocks and drilling line: Blocks refers to the crown block on top of the mast and the travelling block which have sheaves through which the drilling line is reeved. Attached to the travelling block is the hook and the elevators. The hook suspends the drillstring and the elevators are used when running or pulling the drillstring or casings into or out of the hole. The principal function of the blocks and the drilling line is to provide mechanical advantage while raising and lowering extremely heavy loads into the wellbore.
- Deadline anchor and the reserve drum: The deadline anchor is where the drilling line is secured after it has been reeved in the blocks. The deadline anchor and the dead line are stationary. The reserve drum is where the extra length of the drilling line is stored. Figure 2 (Azar, 2007) shows the diagram of the hoisting system.

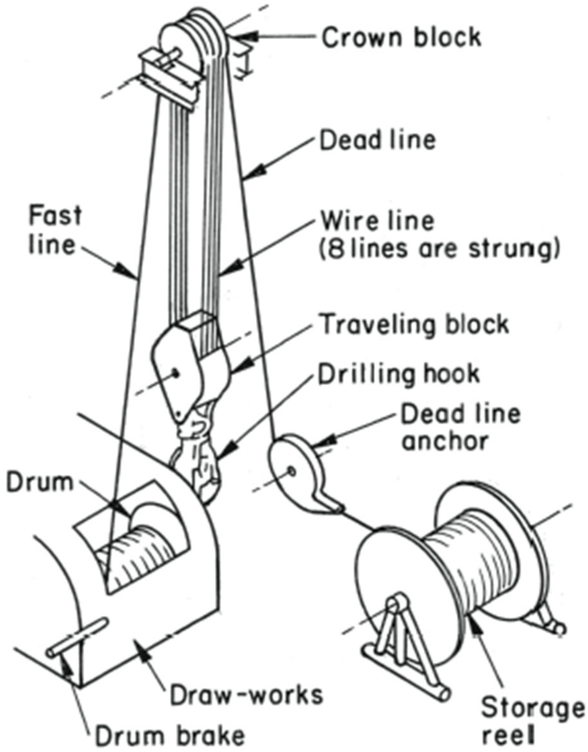

FIGURE 2: The hoisting system

2.2.3 The circulation system

The function of the circulation system is to pump the drilling fluid down through the drillstring and up the annulus, carrying the cuttings from the bottom to the surface (Ford, 2004). Tanks are required for storage, mixing and cleaning the mud. The main components of the circulation system are:

- Mud pumps;
- Air compressors;
- High pressure surface connections;
- Drill string;
- Drill bit;
- Return annulus;
- Mud tanks and pit;
- Mud cleaning equipment.

2.2.4 Rotary system

The rotary system refers to all components used to turn the drillstring and hence the drill bit at the bottom of the hole as shown in Figure 3 (Ford, 2004). These include:

- The swivel;
- Kelly/rotary hose;
- The kelly;
- The rotary table or top drive;
- The drillstring;
- Downhole motors.

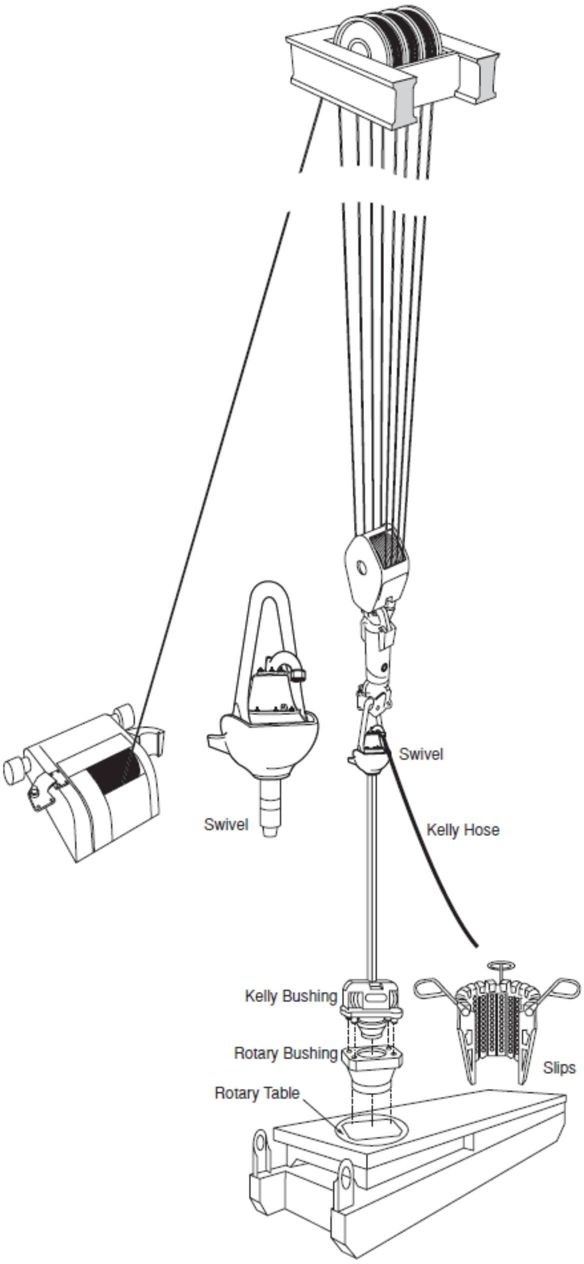

FIGURE 3: The rotary system

2.2.5 Blowout control system

The primary function of the well control system is to prevent the uncontrolled flow of formation fluids from the wellbore as a result of a kick (Azar, 2007). A kick occurs when drilling is done in a permeable formation and the pressure from the pores of the formation is greater than the pressure exerted by the column of the drilling fluid resulting in formation fluids entering the wellbore and displacing the drilling fluid (WHU, 2004). Failure to contain a kick will result to a blow-out which results to higher drilling costs, waste of natural resources, possible loss of human life and damage to equipment.

The primary well control is achieved by ensuring that the hydrostatic drilling fluid pressure is sufficient to overcome the formation pressure. The well control system requirement is to safely permit shutting in the well at surface, controlling removal of formation fluid from the wellbore, pumping high density mud into the hole, and stripping the drill pipe into or out of the hole (Azar, 2007).

The well control system is designed to:

- Detect a kick;
- Close in the well at surface;
- Remove the formation pressure from the well;
- Make the well safe.

The basic components of the well control system is the blowout preventer (BOP) stack shown in Figure 4 which comprises of the following equipment:

- Annular preventer;
- Ram preventers;
- Spools;
- Internal preventers;
- Casing head;
- Flow and choke lines and fittings;
- Kill lines and connections;

- Mud and gas handling facilities;
- Accumulators.

2.2.6 Drilling data acquisition and monitoring system

FIGURE 4: BOP Stack

The purpose of this system is to aid the driller and to monitor, analyse, display, record, and retrieve information regarding drilling operations in order to detect drilling problems for early remedial action. The parameters monitored are drilling rate, hook load, hole depth, pump pressure, flow rate, torque, rotary speed, mud tank levels, pump strokes, weight on bit, and hoisting speed (Azar, 2007). The driller must be aware of how the drilling parameters are changing and their implications (Ford, 2004). The data is stored on the hard disk of the computer system. This information can later be retrieved for the purpose of analysis and research.

2.3 Well planning

The purpose of well planning is to drill a well safely, at a minimum cost and a well that is usable. However because of formation challenges, the drilling equipment, temperature, casing limitations, hole size and budget, it's not always possible to drill according to the well plan (Lake, 2006). Planning for drilling a well requires many detailed studies and evaluating every aspect that directly or indirectly influences the successful outcome of the project. A good well plan requires coordination of the multidiscipline that includes the drilling engineers, drilling supervisors, geoscientists, production engineers, reservoir engineers, safety personnel, environmental scientists, and government inspectors (Azar, 2007).

According to Azar, 2007, well planning involves the following:

- Area geology;
- Casing and cementing program;
- Drilling fluid and the hydraulics program;
- Well control;
- Bottom hole assemble (BHA);
- Drill bit program;
- Routine drilling practices;
- Drilling time curve;
- Drilling rig specifications.

2.3.1 Well design

It is not possible to drill a well through all formations from the surface to the target depth in one uniform hole section. The well is drilled in sections with each section of the well being sealed off by lining the inside of the borehole with a steel pipe known as the casing and filling the annular space between the casing and the borehole with cement. The subsequent section of the borehole with a smaller diameter is then drilled (Ford, 2004). The casing is the major structural component of a well. The following are the reasons for casing off formations:

- To prevent unstable formations from caving into the borehole;
- To isolate zones with abnormally high pore pressure from deeper zones which may have normal pressures;
- To isolate cold zones from deeper hot zones which may quench the well;
- To seal off loss circulation zones;
- To provide structural support for the wellheads and BOPs.

2.3.2 Casing program

A casing string consists of individual joints of steel pipe (casing) which are connected together by threaded connections. Typically a well has six basic types of casing strings, what is referred to as the casing program:

Conductor casing: This is the first casing string run to protect the loose near surface formations. Its function is to seal off unconsolidated formations at shallow depths which with continuous fluid circulation would be washed away (Lake, 2006). In areas where the formations are stronger and less likely to be eroded, the conductor casing may not be necessary. The conductor casing is of the largest diameter (30" outside diameter) in a well and is usually set at depths of up to 30 m for oil and gas drilling (Ford, 2004). In geothermal drilling the conductor casing is usually placed during the construction of the cellar and is usually of up to 4 m in length.

Surface casing: The surface casing is set to provide support for wellhead and Blowout Preventer (BOP) equipment, isolate water sands and prevent lost circulation. It also provides adequate shoe strength to drill into high pressure transition zones (Lake, 2006). The setting depth of this casing is important in an area where abnormally high pressures are expected. If the casing is set too high, the formation below the casing may not have sufficient strength to allow the well to be shut in and killed if a kick is encountered in the next section (WHU, 2004).

Intermediate casing: The intermediate casing is used to isolate unstable hole sections, lost circulation zones, low pressure zones, and production zones (Lake, 2006). This casing isolates troublesome formations between the surface casing depth and the production casing depth (Ford, 2004). In some wells several intermediate casings are installed depending on the number of problem zones encountered (Lake, 2006). For geothermal wells the final casing head flange and master valve is attached to the intermediate casing and serves as the main pressure barrier. The intermediate casing is also called the anchor casing.

The production casing: This casing is set just above the pay zone. The production casing forms the conduit for the geothermal fluid. The production casing need to have a good cement job because it's exposed to high temperatures and pressures (Lake, 2006).

Liner: The liner is suspended from the production casing string or stands on bottom. It is perforated for the full length of the open hole section to allow the geothermal fluid to enter the well.

The chart in Figure 5 is used to select the casing sizes and hole size to be drilled. For example using the Menengai Field in Kenya casing design, 30" casing is used as the conductor casing which is usually installed when the drilling pad is prepared. The surface hole size will be 26" and the surface casing size will be 20". The intermediate hole size will be 17.5" and the intermediate casing size will be 13.375".

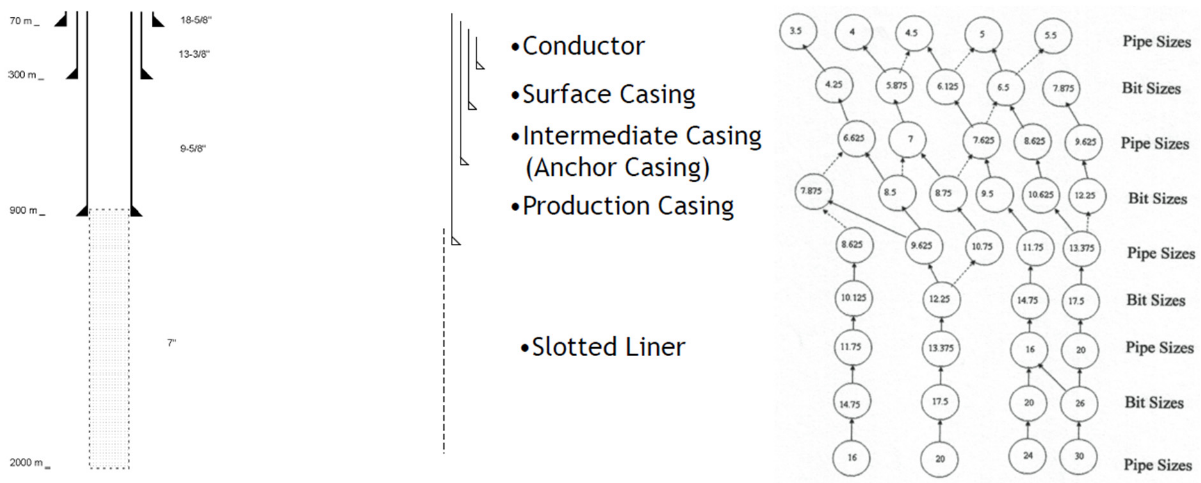

FIGURE 5: Casing depth, size, names, and chart to select the casing and bit sizes

The production hole size will 12.25” while the production casing will be 9.625. Finally the open hole size will be 8.5” and the slotted liner will be 7”.

2.3.3 Geothermal well design

The most critical aspects of geothermal well design is the casing program. It involves the selection of casings, casing specification, determination of casing shoe depths, and how the well is completed. The shallower and the outer casing strings are necessary for drilling operations, while the inner strings are required for production purposes. The surface and conductor casings are set at shallow depths to prevent loose formation from collapsing into the hole. The intermediate or anchor casing is usually set to hold the wellheads permanently and to contain formation and formation fluids that are of relatively high temperatures and pressure. The production casing is of smaller diameter and is set at deeper depths and its function is to deliver the geothermal steam and water to the surface. It is also important in facilitating drilling to the target depth by blocking off leakages of fluids from or to the different aquifers. The depth of setting the production casing is chosen on the basis of what fluids to exclude, usually based on a minimum formation temperature (Hole, 2010).

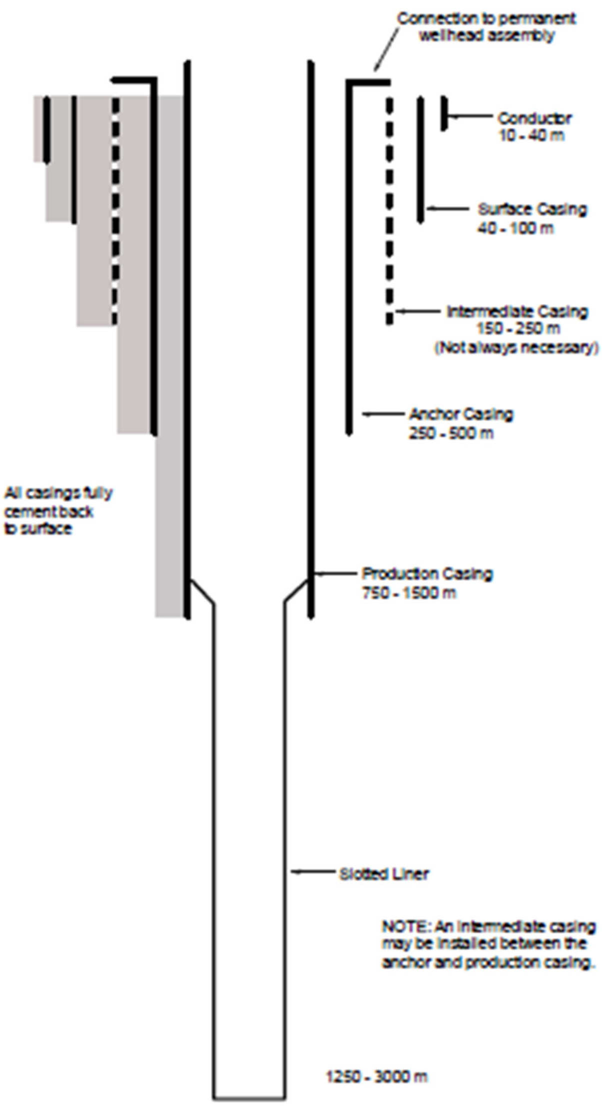

FIGURE 6: A typical geothermal well design

The conductor, surface, anchor, and production casings are all cemented from the casing shoe to the surface. The final casing string called the liner is run within the production section of the well. The liner is usually perforated, slotted or holed and it is run to cover the entire production section. This is because it is difficult to determine the exact permeable zones of the production section of the hole. The liner is not cemented but it is either hung from the production casing or set at the bottom of the well. The top of the liner is usually 20-40 metres inside the production casing shoe and it’s free to move as per the expansion and contraction conditions. Figure 6 shows a typical design of a geothermal well (Hole, 2010).

2.4 Bottom Hole Assembly

The drillstring consists of the tubular and accessories on which the drill bit is run and is made up of two major sections:

- The standard drill pipe and the heavy weight drill pipe (HWDP);
- The bottom hole assembly (BHA).

The BHA consists of the drill collars, stabilizers and the drill bit. In directional wells, the BHA also includes a mud motor. The planed trajectory, vertical or directional, of the well being drilled will determine the type of BHA to be included. In many drilling operations the following are the components found in the BHA:

- The drill collars;
- Stabilizers;
- Reamers;
- Shock absorbing tools;
- Drilling jars;
- Directional tools;
- Information gathering tools (MWD);
- Non-metallic tools;
- Mud motors;
- Crossover subs.

Figure 7 (Ford, 2010) shows the make-up of a drill string.

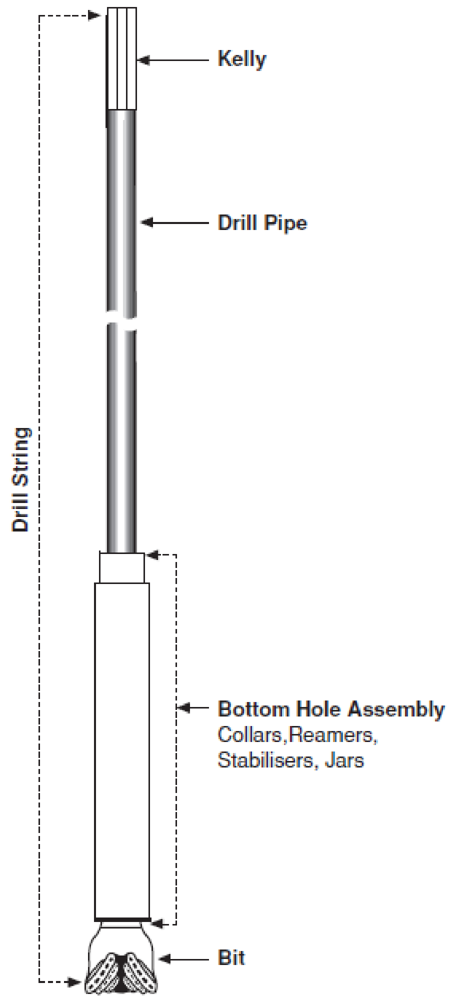

FIGURE 7: Drillstring make up

2.5 Drilling geothermal wells in Menengai, Kenya

Geothermal wells are drilled for three major reasons; for exploration, for resource assessment and for production. The wells principal casing programs are for: large diameter wells, regular diameter wells or slimhole wells. Large diameter wells and regular diameter wells are usually drilled for production purposes and they are costly to drill. Drilling production size holes for geothermal exploration and resource assessment puts a large expense at the beginning of the project, and thus requires a long period of debt service before the costs can be recovered through power sales. Slimholes are drilled because they are less costly and can be used for exploration and resource assessment. Figure 8 below shows the design of the three principal types of geothermal wells.

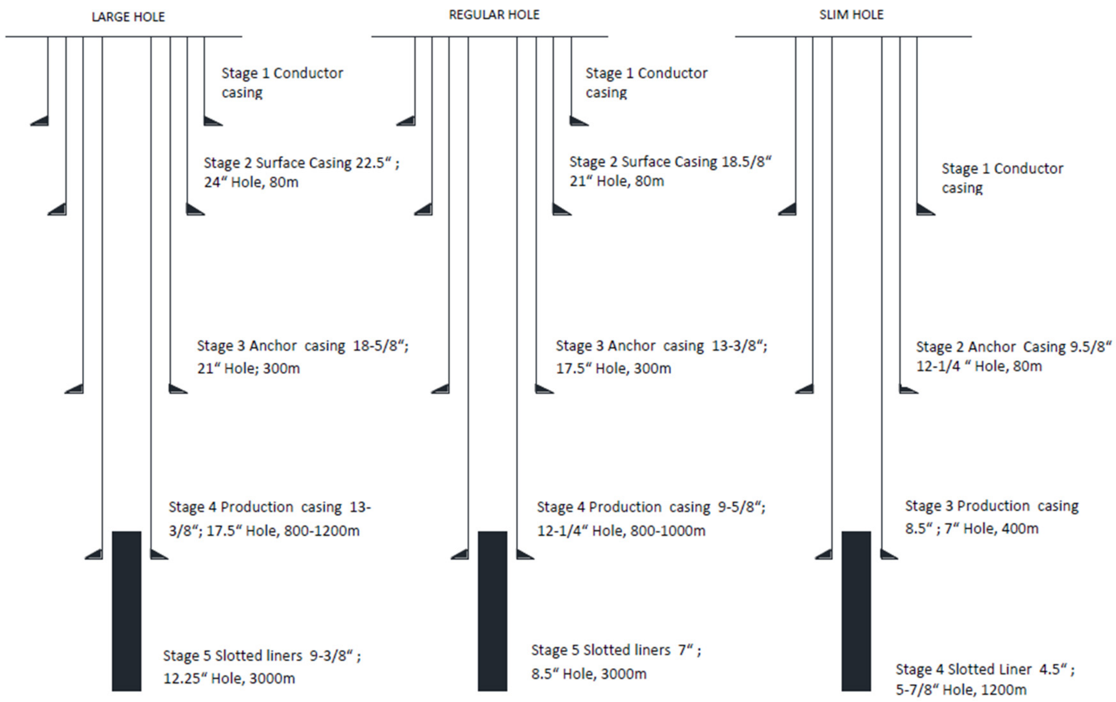

FIGURE 8: Types of geothermal wells and casing design

Wells drilled in the Menengai Geothermal field are of the regular diameter type with a $9^5/_8$" production casing. 2000 HP rigs (some rigs are top drive while others use the kelly) are used with three mud pumps each rated at 1193 kW with a maximum delivery pressure of 34.5 MPa. A typical design of wells in Menengai is as shown in Table 1 and Figure 9. The drilling of the surface hole is characterized with slow rate of penetration (ROP) and a level of vibrations. The intermediate hole is characterized with low rate of penetration and occasional loss of circulation. The production hole has good drillability with occasional loss of circulation. Stuck pipe is also experienced in this section of the well especially at depths around 2000 m where several wells have encountered magma. Down to depths of 1200 m, the fluids used in drilling are water and mud (bentonite). The production hole is drilled with aerated water to achieve pressure balance drilling.

TABLE 1: Typical design of Menengai geothermal wells

Stage of well	Depth	Hole size	Casing size
Stage 1: Surface hole	0-80 m	26´´	20´´
Stage 2: Intermediate Hole	80-400 m	17.5´´	13-3/8´´
Stage 3: Production Hole	400-1200 m	12.25´´	9-5/8´´
Stage 4: Open Hole	1200-3000 m	8.5´´	7´´ Liner

Well MW-17 was spudded on 24th June 2013 and completed on 24th October 2013. A total of 121 days were used to drill the well to completion. The first stage of the well was drilled to 82.57 m and the surface casing was set at 68.37 m. The second stage was drilled to 409 m and the casing anchor casing was set at 403.64m. The third stage was drilled to 1010 m and the production casing was set at 1004.5 m. The fourth stage was drilled to 2218 m and slotted liner was installed. (MW-17 Completion report, 2013). The well profile for a typical Menengai well is as shown in Figure 9. The depths shown are for well MW-17.

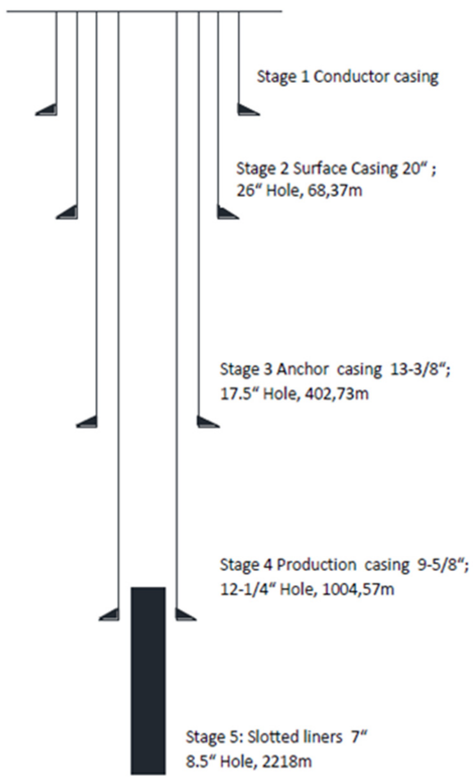

FIGURE 9: Typical well profile for Menengai wells and casing design

3. MODEL THEORY

The aim of this study is to model a drilling rate penetration using the parameters applied to make drilling possible. After creating the drilling rate model, the parameters will be optimized. In creating the drilling model a statistical approach of Multiple Linear Regression has been used to compute the regression constants which are used to calculate the rate of penetration using Equation 1. A computer program using MatLab software has been used do the regression to get the regression constants. Excel spread sheet has been used to do the initial data processing and also to do calculations of the rate of penetration for all sections of the well by using constants from the MatLab program.

3.1 Methodology

To model the drilling operation requires that all factors that affect drilling to be presented in mathematical equations that are derived either from first principles or from experiments. Optimization of drilling should take into account all the factors within and outside the well bore that have a composite effect on the rate of penetration. The following factors have been identified as the major factors that affect the rate of penetration (ROP):

- Formation strength;
- Formation depth;
- Formation compaction;
- Pressure differential across the hole bottom;
- Bit diameter and weight on bit;
- Rotary speed;
- Bit wear;
- Bit hydraulics.

The drilling model taking into account the mentioned factors was first made by Bourgoyne and Young, 1974. This model has been adapted for modelling the rate of penetration and also optimization of the selected parameters. Bourgoyne and Young modelled the rate of penetration into one equation as shown in Equation 1 below:

$$\frac{dh}{dt} = e^{\left(a_1 + \sum_{j=2}^{8} a_j x_j\right)} \tag{1}$$

where $\frac{dh}{dt}$ = Rate of penetration;
h = Depth, ft;
t = Time, hrs;
a_j = Constants;
x_j = Drilling parameters.

The constants 'a_i' and 'x_i' are discussed in detail in Sections 3.1.1 to 3.1.7.

3.1.1 Effect of formation strength

The elastic limit and the ultimate strength of the formation are the most important formation properties affecting rate of penetration. The shear strength of the formation predicted by the Mohr failure criteria is used to determine the strength of the formation. The threshold force required to initiate drilling could be related to the shear strength of the rock as determined in the compression test at atmospheric pressure (Bourgoyne et al., 1991). The effect of formation strength in Equation 1 is given by the constant a_1. The Constant a_1 also includes the effect of drilling variables such as mud type, solid contents etc. which have not yet been mathematically modelled (Bourgoyne et al., 1974).

3.1.2 Effect of formation compaction

The effect of normal formation compaction and under compaction of formation is represented by coefficients a_2 and a_3 respectively. The compaction effect on rate of penetration x_2 assumes an exponential decrease in ROP with depth for a normally compacted formation. x_3 assumes an exponential increase in the penetration rate with pore pressure gradient. The function x_2 accounts for the increase in rock strength due to normal compaction with depth and x_3 accounts for the effect of under-compaction experienced in abnormally pressured formations, (Bourgoyne et al., 1991). The effect of formation compaction on the rate of penetration is modelled by x_2 and x_3 as shown below:

$$x_2 = 10000 - h \tag{2}$$

$$x_3 = h^{0.69}(g_p - 9) \tag{3}$$

where g_p = Pore pressure gradient of the formation.

3.1.3 Effect of pressure differential across the bit

The constant a_4 gives the effect of pressure differential at the bottom of the hole. The function x4 models the effect of overbalance on penetration rate. It assumes exponential decrease in penetration rate with excess bottom-hole pressure. This function is zero when the formation pressure is equal to the bottom hole pressure in the well. (Bourgoyne et al., 1991). The effect of pressure differential across the bit on the rate of penetration is modelled by x_4 and is given by Equation 4:

$$x_4 = h(g_p - \rho_c) \tag{4}$$

where ρ_c = Equivalent circulating mud density at the bottom hole.

3.1.4 Effect of bit diameter and weight on bit, (w/d)

The constant a_5 gives the effect of weight on bit and bit diameter. The function X_5 assumes that penetration rate is directly proportional to $(w/d)^{a_5}$ (Bourgoyne et al 1974). The threshold bit weigh is the weight at which the bit begins to drill. When the weigh is subsequently increased on the bit, the teeth of the bit transmit a shear force to the rock and when the shear strength of the rock is exceeded, the rock fractures. The force at which fracturing begins beneath the tooth is called the threshold force. The weight below the threshold bit weight cannot shear the rock. The threshold bit weight for a given formation type is determined by drill off tests. The threshold weight required to initiate drilling is obtained by plotting drilling rate as a function of bit weigh per bit diameter and then extrapolating back to a zero drilling rate (Bourgoyne et al., 1991). For this study such data was not available and the threshold values applied were based on published data for the different types of volcanic rock formations (Xiao et al., 2011). The effect of weight on bit and bit diameter on rate of penetration is modelled by x_5 as shown in Equation 5 below:

$$x_5 = ln\left(\frac{\frac{w}{d} - \left(\frac{w}{d}\right)_t}{4 - \left(\frac{w}{d}\right)_t}\right) \tag{5}$$

where w/d = Weight on bit (WOB) per inch of bit diameter, 1000 lb/in;
$(w/t)_t$ = Threshold weight on bit (WOB) per inch of bit diameter.

3.1.5 Effect of rotary speed, N

The constant a_6 gives the effect of rotary speed. The function x_6 assumes that penetration rate is directly proportional to rotation speed of the bit. Penetration rate usually increases linearly with rotary speed at low values of rotary speed. At higher values of rotary speed, the response of penetration rate to increasing rotation of the bit diminishes. This is attributed to poor bottom hole cleaning due to high rate of generation of cuttings (Bourgoyne et al., 1991). The effect of rotary speed is modelled by x_6 as shown in Equation 6 below:

$$x_6 = ln\left(\frac{N}{100}\right) \tag{6}$$

where N = Rotations per minute (RPM).

3.1.6 Effect of tooth wear

The constant a_7 models the effect of tooth wear on penetration rate. Most bits tend to drill slower as the teeth of the bit wear out. For milled tooth rolling cutter bits, the tooth wear of and chip off due to the abrasion of the formation. For tungsten Carbide insert bits, the tooth fail by breaking of rather than by abrasion. Reduction in rate of penetration for tungsten carbide insert bits is not as severe as for milled tooth bits. (Bourgoyne et al., 1991). When carbide insert bits are used, the penetration rate does not vary significantly with tooth wear and thus the tooth wear exponent a7 is assumed to be zero (Bourgoyne et al., 1974). This is the case of drilling in Menengai where Tungsten Carbide Insert (TCI) bits are used, the term t_w has been put to zero when regressing the data, and hence the result of the regression for a_7 is shown as zero. The function x_7 models the effect of tooth wear on penetration rate as shown in Equation 7:

$$x_7 = -t_w \tag{7}$$

where t_w = The fractional tooth height that has been worn away.

3.1.7 Effect of bit hydraulics

The a_8 coefficient shows effect of the hydraulics function on penetration rate. X_8 assumes that the ROP is proportional to a Reynolds number group $(\frac{\rho q}{\mu d_n})^{0.5}$. The Reynolds number group gives the effect of the jetting action of the drilling fluid at the bottom which promotes better bit teeth cleaning and hole cleaning. At low bit weight and penetration rate, the level of hydraulics needed for bottom hole cleaning is small. As more weight is added and more cuttings are generated faster, floundering is reached and the cuttings generated are not evacuated as fast as they are generated (Bourgoyne et al., 1991). The effect of hydraulics is modelled by x_8 as shown in Equation 8a:

$$x_8 = \frac{\rho q}{350\mu d_n} \tag{8a}$$

where ρ = Density, lb/gal;
q = Discharge, gal;
μ = Apparent viscosity at 10000 sec^{-1}, cp;
d_n = Nozzle diameter, inches.

This value can be estimated by Equation 8b:

$$\mu = \mu_p + \frac{\tau_y}{20} \tag{8b}$$

Modelling for the rate of penetration combines the effects of the parameters discussed in section 3. Actual data from the well being drilled is used to determine the coefficient s a_i and x_i. These coefficients are then used to predict the rate of penetration for the next section of the well to be drilled or another well within the field where the data was taken from. For a given section of the well being modelled, the formation has to be homogenous.

3.2 Optimization of selected parameters

The optimization of the parameters in this model is done using the mathematical equations derived for them. Three parameters will be optimized: the bit weight, the rotary speed and bit hydraulics. The Weight on Bit (WOB) and Rotation per Minute (RPM) are important controllable parameters that can be easily manipulated at the rig. Bit hydraulics can also be manipulated by controlling the nozzle diameter, the drilling fluid type and the pumping rate.

3.2.1 Optimizing weight on bit

According to Eren, 2010, optimization can be done by adjusting the magnitude of two or more independent parameters. In drilling this can be achieved by means of minimizing cost per foot drilled or by minimizing problems. The optimized WOB lies within the minimum WOB (determined by the threshold weight on bit) and the maximum WOB (determined by the design of the bit). The optimization of WOB depends on the drilling cost per foot as shown in Equation 9 below (Bourgoyne et al., 1974):

$$C_f = \frac{C_b + C_r(t_t + t_c + t_b)}{\Delta h} \tag{9}$$

where C_f = Drilling cost per foot;
C_b = Bit cost;
C_r = Hourly rig rate;
t_t = Trip time;
t_c = Connection time;
t_b = Drilling time;
Δh = Footage drilled.

Combining Equations 9, 1 and the properties of the bit, then differentiating and equating to zero results to Equation 10 below for optimum weight on bit (Eren, 2010):

$$\left(\frac{W}{d_b}\right)_{Opt} = \frac{a_5 H_1 \left(\frac{W}{d_b}\right)_{max} + a_6 \left(\frac{W}{d_b}\right)_t}{a_5 H_1 + a_6} \tag{10}$$

Where $(W/d_b)_{Opt}$ = Optimum weight on bit per bit diameter;
$(W/d_b)_{max}$ = Maximum weight on bit per bit diameter;
$(W/d_b)_t$ = Threshold weight on bit per bit diameter;
a5 & a6 = Regression constants;
H_1 = Constant that depends on bit type.

3.2.2 Optimizing rotations per minute

Similarly the optimum RPM is found in the same way as Equation 10 and is as shown below in Equation 11 (Bourgoyne et al., 1974):

$$(N)_{Opt} = 100 \left(\frac{\tau_H}{t_b} \frac{\left(\frac{W}{d_b}\right)_{max} - \left(\frac{W}{d_b}\right)_{Opt}}{\left(\frac{W}{d_b}\right)_{max} - 4} \right)^{\frac{1}{H_1}} \tag{11}$$

Where N_{opt} = Optimum RPM;
τ_H = Formation abrasiveness constant;
t_b = Rotating time.

The formation abrasiveness constant is given as shown in Equation 12 below:

$$\tau_H = H_3 \frac{N}{100} H_1 \left(\frac{\left(\frac{W}{d}\right)_{max} - 4}{\left(\frac{W}{d}\right)_{max} - \frac{W}{d}} \right) \left(\frac{1 + \frac{H_2}{2}}{t_w + \frac{H_2 {t_w}^2}{2}} \right) t_b \tag{12}$$

where H_2 & H_3 are constants that depend on bit type.

The rotating time t_b is given by Equation 13 below:

$$t_b = \left(\frac{C_b}{C_r} + t_t + t_c\right)\left(\frac{H_1}{a_6} - 1\right) \tag{13}$$

4. DATA ANALYSIS

From the methodology section, several variables ae needed as input to the model. Some of the variables are parameters that are captured as the well is drilled. Some of the variables need to be calculated using mathematical formulae while others need to be got using field measurements under special conditions. The parameters required for the model are as shown in Table 2 below:

TABLE 2: Variables needed for the model

Variables measured while drilling	Variables to be calculated	Variables that need special field test/measurements
Depth Rate of penetration (ROP) Weight on bit (WOB) Rotary speed (RPM) Flow rate	Equivalent circulation density Pore pressure gradient	Threshold weight on bit Bit and nozzle diameter Fluid viscosity Density of fluid Tooth wear fraction

In order to calculate the equivalent circulation density and pore pressure gradient, pressure losses calculations in the wellbore is needed. The background on the calculations is discussed under the hydraulics and hydraulics models. This section will require use of bit and nozzle diameters, fluid viscosity and fluid density. This is discussed in detail in section 4.1and 4.2.

4.1 Hydraulics

The main functions of drilling fluids include: cleaning the hole and transporting the cuttings to the surface, supporting and stabilizing the walls of the wellbore during drilling, minimize kicks by balancing or overcoming the formation pressures, cooling and lubricating the bit and the drill string, and transmitting hydraulic horsepower to the mud motor and bit. For the drilling fluid to perform the stated functions, it has to have sufficient flow and pressure which is provided by the mud pumps. A significant amount of power is used to overcome frictional forces (resistance to flow) primarily inside the drill string, but also in the annulus and through the bit nozzles.

The resistance to flow is expressed in terms of the amount of pressure drop required to circulate the fluid round the system and is called the circulating pressure of the system. The hydraulic power expended when circulating the fluid is a direct function of the pressure losses and the flow rate through the system. The pressure required to circulate the fluid through the drill string and the annulus is referred to us the sacrificial pressure losses since the do not contribute anything to the drilling process but cannot be avoided since the fluid has to be circulated around the system. The ejection of the drilling fluid through the nozzles of the bit also results in significant pressure loss but does perform a useful function of cleaning the drilled cuttings from below the bit. To the drilling process, it is desirable to optimize pressure losses through the bit nozzles and minimize pressure losses in the drill string and annulus (Ford, 2004).

Mud hydraulics is one of the most important factors affecting mud drilling performance. The rate of penetration can be increased by optimization of the mud hydraulics thus taking less time to complete drilling the well hence reducing drilling operational costs. The essence of hydraulics optimization is to utilize the pumps power to the maximum to help the bit to drilling at maximum efficiency. This is achieved by minimizing losses inside the drill string and in the annulus and using the saved energy in improving bit hydraulics (Guo, 2011).

4.1.1 Rheological models

Rheology is the science that’s concerned with the deformation of matter but has had greatest development in the study of the flow behaviour of suspensions in pipes and other conduits. Study of flow behaviour entails the relationship between the pressure and flow rate of the fluid. (Lyons et al., 2005). The flow or deformation is studied in terms of shear rate and shear stress. Shear rate is the flow velocity gradient in the direction perpendicular to the flow direction whereas shear stress is the force per unit area of shearing layer. The higher the shear rate the higher the friction between the flowing particles.

There are fundamentally two different flow characteristics; laminar flow in which flow is orderly and the pressure velocity relationship is a function of the viscous properties of the fluid and turbulent flow which is disorderly and is governed primarily by the inertial properties of the fluid in motion (Guo, 2011). Fluids are classified according to the different categories in rheological studies on the basis of their flow behaviours. The different types of fluids used in the drilling industry can be classified under one of these flow models: Newtonian, Bingham plastic, the pseudoplastic, the yield power law (also known as the Herschel-Bulkley), and the dilatant. The behaviour of these models is shown in Figure 10 (Guo, 2011). The behaviour shown is valid only in laminar flow.

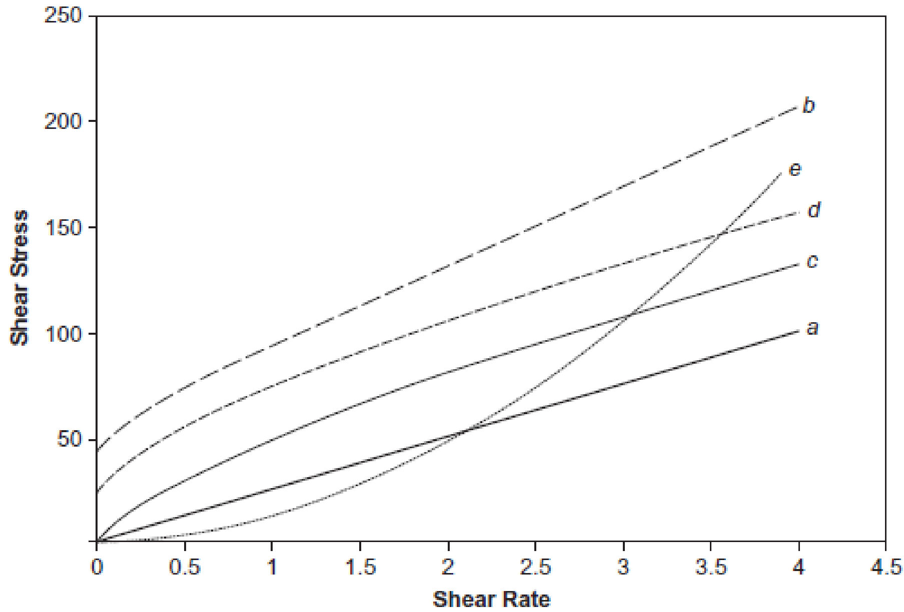

FIGURE 10: behaviour of different types of drilling fluids

4.1.2 Newtonian fluids and models

Newtonian fluids are the most common in nature. The shear stress is proportional to the shear rate meaning that the flow resistance increases linearly with flow deformation and this is valid only for laminar flow. Water, brines, gases and oil are examples of these fluids. This is shown in curve *a* Figure 10 above. The rheological model for the Newtonian fluids is expressed in Equation 14 below:

$$\tau = \mu \gamma \tag{14}$$

where τ = Shear stress, Pa;
μ = Viscosity, Pa-s;
Υ = Shear rate, s^{-1}.

4.1.3 Bingham plastic fluids and models

Bingham fluids require a finite shear stress τ_y, referred to as yield point, to be applied on them before they can flow and below that stress they will not flow. Above the yield point the Bingham fluids behave like the Newtonian fluids. Bingham fluids are represented by curve *b* in Figure 10 above. The rheological model for Bingham fluids is shown in Equation 15 below:

$$\tau = \tau_y + \mu_p \gamma \tag{15}$$

where τ_y = Yield point, Pa;
μ_p = Plastic viscosity, Pa-s.

4.1.4 Pseudoplastic/power law fluids and models

The fluids have a non-linear relationship between the shear rate and the shear stress. The flow resistance increases less than linearly with deformation as shown by curve *c* in Figure 10. The rheological model for pseudoplastic fluids is shown in Equation 16 below. Polymer solutions usually fall in this category:

$$\tau = \mathrm{K}\gamma^{n} \text{ and n<1} \tag{16}$$

where K = Consistency Index, Pa-s;
N = Power law index, dimensionless.

A term μ_a that is called apparent viscosity is defined by the Equation 17 as shown below:

$$\mu_a = K\gamma^{n-1} \tag{17}$$

The apparent viscosity decreases as the shear rate increases for power law fluids.

4.1.5 Yield power law/Herschel-Bulkley fluids and models

Yield power law fluids require a finite shear stress τ_y, referred to as yield point, to be applied on them before they can flow and below that stress they will not flow as shown in Figure 10 curve *d*. Above the yield point, the shear rate is related to the shear stress through a power-law type relationship. The rheological model for Herschel-Bulkley fluids is shown in Equation 18 below:

$$\tau = \tau_y + K\gamma^{m} \tag{18}$$

where K = Consistency index, Pa-s;
m = Power-law index, dimensionless;
τ_y = Yield point, Pa.

4.1.6 Dilatant fluids and models

The Dilatant fluids show a nonlinear relationship between the shear rate and the shear stress. The flow resistance increases greater than linearly with deformation as shown in curve *e* in Figure 10 above. When plotted on a log-log paper, the shear stress and shear rate show a linear relationship. The apparent viscosity for these fluids increases as shear rate increases. Examples of dilatant fluids include quick sand and Newtonian fluids mixed with starch like materials. The rheological model for Dilatant fluids is shown in Equation 19 below:

$$\tau = K\gamma^{n} \text{ and n > 1} \tag{19}$$

Fluids that exhibit direct proportionality between shear stress and shear rate are classified as Newtonian fluids. Fluids that do not exhibit direct proportionality between shear stress and shear rate are classified as non-Newtonian fluids. Non-Newtonian fluids that are used in drilling are the plastic and pseudoplastic fluids under the Bingham plastic and Power law models. The Herschel-Bulkley model is widely used theoretically in designing fluid hydraulics (Guo, 20011).

4.2 Hydraulic Models

The flow behaviour of drilling fluids can be described using mathematical models called hydraulics models. The models give a correlation between flow rates and pressure drop for a given geometry of flow conduit, fluid properties, and flow regime (Guo, 2009).

Flow in pipes and annuli are characterized as laminar or turbulent flow. Laminar flow can be solved analytically using mathematical models. For turbulent flow the correlation is developed empirically by developing experiments in a flow loop (Lake, 2006) A large amount of experimental work has been done in pipes and annuli and factors influencing onset of turbulence and frictional pressure losses due to turbulent flow have been identified (Ford, 2004).

While drilling, it is preferred to see laminar flow in the annulus to move cuttings up the hole and to prevent erosion. Turbulent flow is more desirable at the bottom of the hole because this promotes cleaning and removing of cuttings from the face of the bit. Practically, fluid behaviour varies within the circulating system and more than one flow regime may exist at the same point in the circulation system (Guo, 2011).

In analysing flow experimentally, two dimensionless numbers are usually correlated for the various types of fluids discussed. These numbers are the Fanning friction factor (*f*) and the Reynolds number (Re). The relationship between the friction factor and the Reynolds number under the laminar and turbulent flow regimes for the various rheological models is discussed below and forms the basis for the hydraulic models.

4.2.1 Pressure losses for the various hydraulic models

The circulation system, the drilling fluid is pumped to the drilling bit from the surface down the drill string and out through annulus. The mud pumps provide the required power for the fluid circulation and they have to overcome frictional forces between the fluid layers, the solid particles, the pipe wall and the borehole wall. The friction between the fluid layers and the walls of the pipe and hole causes pressure losses. Pressure available at the bit is usually far much less than the pressure provided by the pump at the surface because most of it is lost due to friction.

According to Guo, 2011, the pump pressure corresponds to the sum of all pressure losses as shown in Equation 20 below:

$$P_p = \Delta p_s + \Delta p_{dp} + \Delta p_{dc} + \Delta p_{mt} + \Delta p_b + \Delta p_{dca} + \Delta p_{dpa} \tag{20}$$

where P_p = Pump pressure, Pa;
Δp_s = Pressure loss in the surface equipment, Pa;
Δp_{dp} = Pressure loss in the drill pipe, Pa;
Δp_{dc} = Pressure loss in the drill collar, Pa;
Δp_{mt} = Pressure drop in the mudmotor, Pa;
Δp_b = Pressure drop at the bit, Pa;
Δp_{dca} = Pressure loss in the drill collar annulus, Pa;
Δp_{dpa} = Pressure loss in the drill pipe annulus, Pa.

In drilling, the pump pressure, P_p in Equation 21, required to drill a certain section of the well is equal to total friction pressure losses P_f, (summation of Δp_s , Δp_{dp}, Δp_{dc}, Δp_{dpa}, and Δp_{dca}) plus dynamic pressure changes, P_B (summation of Δp_{mt}, Δp_b) (Azar, 2007):

$$P_p = P_f + P_B \tag{21}$$

The surface equipment consists of the standpipe, the rotary hose, the swivel, and the Kelly pipe. In field applications, the total pressure loss is not calculated based on the geometry of each piece of equipment but it is estimated using an equivalent length of drill pipe. Table 3 shows the various inner diameters of the surface equipment and their grouping (Guo, 2011).

TABLE 3: Grouping of surface equipment sizes

	Combination 1				Combination 2				Combination 3				Combination 4			
	ID		Length		ID		Length		ID		Length		ID		Length	
Component	in	cm	ft	m	in	cm	ft	m	in	cm	ft	m	in	cm	ft	m
Standpipe	3	7.6	40	12.2	3.5	8.9	40	12.2	4	10.2	45	13.7	4	10.2	45	13.7
Rotary hose	2	5.1	45	13.7	2.5	6.4	55	16.8	3	7.6	55	16.8	3	7.6	55	16.8
Swivel	2	5.1	4	1.2	2.5	6.4	5	1.5	2.5	6.4	5	1.5	3	7.6	6	1.8
Kelly pipe	2.25	5.7	40	12.2	3.3	8.3	40	12.2	3.3	8.3	40	12.2	4	10.2	40	12.2

The combinations in Table 3 above have equivalent drill pipe lengths as shown in Table 4.

TABLE 4: Equivalent drill pipe length for typical surface equipment combinations

Equivalent Drill Pipe	Combination 1 ft	Combination 1 m	Combination 2 ft	Combination 2 m	Combination 3 ft	Combination 3 m	Combination 4 ft	Combination 4 m
3.5″, 13.3 lb/ft	437	133	161	49				
4.5″, 16.6 lb/ft			761	232	479	146	340	104
5″, 19.5 lb/ft					816	249	576	176

The general procedure for calculating frictional pressure loss is first to determine the Reynolds number at the point of interest and then calculate the critical Reynolds number that will be used to determine the drilling fluid regime of flow and finally using appropriate pressure loss equations based on the rheological model and flow regime of the fluid at the point of interest. The gradient of frictional pressure drop is based on Fanning equation and is as shown in Equation 22 below (Guo, 2011):

$$\frac{dp_f}{dL} = \frac{f\rho v^2}{519d} \tag{22}$$

where p_f = Frictional pressure drop, Pa;
L = Pipe length, m;
f = Fanning friction factor, dimensionless;
v = Average velocity;
ρ = Density, kg/m^3.

4.2.2 Hydraulic model for Newtonian fluids

For Newtonian fluids inside the drill pipe, the Reynolds number is defined as shown in Equation 23 below. The Reynolds number is used for determining the fluids flow regime.

$$Re = \frac{\rho v d}{\mu} \tag{23}$$

where Re = Reynolds number, dimensionless;
ρ = Density, Kg/m^3;
v = Average flow velocity, m/s;
d = Inside diameter of the pipe, m;
μ = Fluid viscosity, Pa-s.

For fluids flowing in the annular:

$$Re = \frac{\rho v(d_1 - d_2)}{\mu} \tag{24}$$

where d_1 = Hole or casing diameter, m;
d_2 = Outside diameter of pipe, m.

The average velocity in both cases is calculated as discharge divided by the cross sectional area of flow.

Generally, Reynolds numbers of less than 2100 indicate laminar flow while Reynolds numbers greater than 4000 indicate turbulent flow. The numbers between these values are considered transitional flow (Guo, 2011).

Pressure drop for Newtonian fluids
The fanning friction factor for Newtonian fluids under laminar flow is as shown in Equation 25 below (Guo, 2011):

$$f = \frac{16}{Re} \tag{25}$$

Combining Equations 25 and 22 result in Equation 26 for frictional pressure drop for Newtonian fluids inside a pipe under laminar flow (Guo, 2011):

$$\Delta p_f = \frac{\mu v}{0.0313 d^2} \Delta L \tag{26}$$

For Newtonian fluids inside the annulus, the pressure drop is calculated using Equation 27 below (Guo, 2011):

$$\Delta p_f = \frac{\mu v}{0.0209 (d_2 - d_1)^2} \Delta L \tag{27}$$

where Δpf = Pressure loss, kPa;
f = Fanning friction factor, dimensionless;
Re = Reynolds number, dimensionless;
μ = Viscosity, Pa-s;
v = Average velocity, m/s;
ΔL = Length of conduit, m;
d = Inside diameter of pipe, m;
d_1 = Outside diameter of pipe, m;
d_2 = Diameter of hole or casing, m.

For turbulent flow of Newtonian fluids, several empirical correlations for determining the Fanning friction factors are available. The Colebrook expression for friction factor is as shown below (Guo, 2011):

$$\frac{1}{\sqrt{f}} = -4 log \left(0.269 \frac{\delta}{d} + \frac{1.255}{Re\sqrt{f}} \right) \tag{28}$$

where δ = Absolute roughness of the pipe surface, m;
d = Diameter, m;
f = Friction factor, dimensionless.

The pressure drop for turbulent Newtonian fluid flow in a pipe is given as shown in the Blasius correlation below:

$$\Delta pf = \frac{\rho^{0.75} v^{1.75} \mu^{0.25}}{631.8 d^{1.25}} \Delta \mathrm{L} \tag{29}$$

For annular turbulent fluid flow:

$$\Delta pf = \frac{\rho^{0.75} v^{1.75} \mu^{0.25}}{490 (d_2 - d_1)^{1.25}} \Delta \mathrm{L} \tag{30}$$

4.2.3 Hydraulic model for Bingham plastic fluids

For Bingham plastic fluids the equations for Newtonian fluids are modified to account for plastic viscosity and yield point. This is done by defining a new term called apparent viscosity that takes into account the plastic viscosity and yield point as shown in Equations 31 and 32 (Guo, 2011). For pipe flow:

$$\mu_a = \mu_p + \frac{0{,}1669 \tau_y d}{v} \tag{31}$$

For annular flow:

$$\mu_a = \mu_p + \frac{0{,}1253 \tau_y (d_2 - d_1)}{v} \tag{32}$$

where μ_a = Apparent viscosity, Pa-s;
μ_p = Plastic viscosity, Pa-s;
τ_y = Yield point, Pa.

Thus for Bingham plastic fluids, Equations 23 and 24 become respectively:

$$Re = \frac{\rho v d}{\mu_a} \tag{33}$$

$$Re = 0.816 \frac{\rho v (d_1 - d_2)}{\mu_a} \tag{34}$$

Pressure drop for Bingham plastic fluids:
The pressure loss for laminar flow inside a drill pipe can be estimated by Equation 35 below:

$$\Delta p_f = \left(\frac{\mu_p v}{0{,}0313 d^2} + \frac{\tau_y}{0{,}1875 d} \right) \Delta L \tag{35}$$

For laminar annular flow:

$$\Delta p_f = \left(\frac{\mu_p v}{0{,}02088 (d_2 - d_1)^2} + \frac{\tau_y}{0{,}1667 (d_2 - d_1)} \right) \Delta L \tag{36}$$

The pressure loss for turbulent flow inside a drill pipe can be estimated by Equation 37 below:

$$\Delta pf = \frac{\rho^{0.75} v^{1.75} \mu_p{}^{0.25}}{631.8 d^{1.25}} \Delta \mathrm{L} \tag{37}$$

For annular turbulent annular fluid flow:

$$\Delta pf = \frac{\rho^{0.75} v^{1.75} \mu_p{}^{0.25}}{490 (d_2 - d_1)^{1.25}} \Delta \mathrm{L} \tag{38}$$

4.3 Data processing

This section discusses how the variables for input into the model were determined from the data captured and measured at the rig and also those variable taken from past research work.

4.3.1 Variables from the rig

The initial data at the rig for well MW-17 is acquired by the Drilling data acquisition and monitoring system. The parameters are stored at 10 second intervals are: drilling rate, hook load, hole depth, pump pressure, flow rate, torque, rotary speed, mud tank levels, pump strokes, weight on bit, and hoisting speed. The data is usually retrieved in Excel tables with the parameters recorded in each columns. A typical raw data retrieved from a Drilling data acquisition and monitoring system for well MW-17 in Menengai is as shown in Table 5 below.

The first step in the data processing was to remove all the parameters that were not needed in the modelling and optimization of the drilling rate. The parameters that are used in the modelling and optimization of the drilling rate as per Equations 1-8 are the depth, rate of penetration (ROP), weight on bit (WOB) and rotations per minute (RPM). These parameters are captured by the data acquisition system. The other parameters needed in the modelling are determined from the properties or from calculations. These parameters are: equivalent circulating density (ECD) at the bottom hole, density of the drilling fluid, the discharge, viscosity of the drilling fluid, yield strength of the drilling mud, pore pressure gradient and the nozzle diameter.

From Table 5, the ROP that are zero were not considered in the modelling. ROP was considered only when the bit was cutting the formation at the bottom of the hole. Data where the WOB is zero or less than zero was discarded. Negative WOB implies that the bit was not in contact with the formation due to vibration. Zero WOB implies that the bit was pulled off bottom probably due to excessive vibration or during circulation and reaming of the well. This will yield data that is captured at the well site as show in Table 6. This data will be used in the modelling after it has been converted to the desired units.

TABLE 5: Part of the raw data for well MW-17

Date and Time	Hole Depth m	Bit Depth m	ROP min/m	WOB 10kN	WOH	Rotary Torque	RPM r/min	PumpPressure1 Mpa	Pump Rate1	Pump Rate2	Pump Rate3	Sum Pump Rate	Flow In	Lineworks
2013.06.25 09:16:04	14,9	14,9	0	0	14,63	0	50,84	0	0	83,69	0	83,86	23,22	2828,49
2013.06.25 09:16:34	14,9	14,9	0	−0,29	14,69	0	50,84	0	0	83,69	0	83,86	23,22	2828,49
2013.06.25 09:17:04	14,9	14,9	0	0	14,46	0	49,99	0	0	84,12	0	84,29	23,34	2828,49
2013.06.25 09:17:34	14,9	14,9	0	0	14,52	0	51,15	0	0	83,16	0	83,33	23,07	2828,49
2013.06.25 09:18:04	14,9	14,9	0	0	14,52	0	51	0	0	84,44	0	84,6	23,43	2828,49
2013.06.25 09:18:34	14,9	14,9	0	0	14,52	0	50,85	0	0	82,84	0	83	22,99	2828,49
2013.06.25 09:19:04	14,9	14,9	0	0	14,63	0	49,67	0	0	84,54	0	84,71	23,46	2828,49
2013.06.25 09:19:34	14,9	14,9	0	0,17	14,23	0	50,84	0	0	82,74	0	82,9	22,96	2828,49
2013.06.25 09:20:04	14,9	14,9	0	0	14,86	0	50,14	0	0	84,44	0	84,6	23,43	2828,49
2013.06.25 09:20:34	14,9	14,9	0	0	14,69	0	51,46	0	0	83,2	0	83,36	23,08	2828,49
2013.06.25 09:21:04	14,9	14,9	0	−0,23	14,63	0	51,01	0	0	84,01	0	84,18	23,31	2828,49
2013.06.25 09:21:34	14,9	14,9	0	0,29	14,12	0	49,82	0	0	83,69	0	83,86	23,22	2828,49
2013.06.25 09:22:04	14,9	14,9	0	0	14,4	0	49,66	0	0	83,69	0	83,86	23,22	2828,49
2013.06.25 09:22:35	14,9	14,9	0	0	14,8	0	50,46	0	0	84,12	0	84,29	23,34	2828,49
2013.06.25 09:23:05	14,9	14,9	0	0	14,86	0	49,35	0	0	83	0	83,17	23,03	2828,49
2013.06.25 09:23:35	14,9	14,9	0	0	14,52	0	50,29	0	0	84,44	0	84,6	23,43	2828,49
2013.06.25 09:24:05	14,9	14,9	0	0	14,29	0	51,46	0	0	82,74	0	82,9	22,96	2828,49
2013.06.25 09:24:35	14,9	14,9	0	0	14,17	0	50,29	0	0	84,54	0	84,71	23,46	2828,49
2013.06.25 09:25:05	14,9	14,9	0	0	14,63	0	51	0	0	83,01	0	83,18	23,03	2828,49
2013.06.25 09:25:35	14,9	14,9	0	0	14,8	0	50,6	0	0	84,29	0	84,45	23,39	2828,49
2013.06.25 09:26:05	14,9	14,9	0	0	14,06	0	49,12	0	0	83,43	0	83,6	23,15	2828,49
2013.06.25 09:26:35	14,9	14,9	0	−0,11	14,52	0	50,14	0	0	83,86	0	84,02	23,27	2828,49
2013.06.25 09:27:05	14,9	14,9	0	0	14,29	0	49,82	0	0	83,7	0	83,86	23,22	2828,49
2013.06.25 09:27:35	14,9	14,9	0	−0,29	14,69	0	49,67	0	0	83,43	0	83,6	23,15	2828,49
2013.06.25 09:28:05	14,9	14,9	0	0	14,92	0	50,61	0	0	84,12	0	84,29	23,34	2828,49
2013.06.25 09:28:35	14,9	14,9	0	−0,92	15,32	0	50,3	0	0	82,84	0	83	22,99	2828,49
2013.06.25 09:29:05	14,9	14,9	0	−0,57	14,98	0	50,3	0	0	84,44	0	84,6	23,43	2828,49
2013.06.25 09:29:35	14,9	14,9	0	0	14,29	0	50,46	0	0	82,84	0	83	22,99	2828,49
2013.06.25 09:30:05	14,9	14,9	0	0	14,92	0	50,45	0	0	84,55	0	84,71	23,46	2828,49
2013.06.25 09:30:35	14,9	14,9	0	−0,57	14,98	0	50,61	0	0	83	0	83,17	23,03	2828,49
2013.06.25 09:31:05	14,9	14,9	0	−0,57	14,98	0	50,6	0	0	84,29	0	84,45	23,39	2828,49
2013.06.25 09:31:35	14,9	14,9	0	−0,11	14,52	0	50,46	0	0	83,59	0	83,75	23,19	2828,49
2013.06.25 09:32:05	14,9	14,9	0	−0,86	15,26	0	50,61	0	0	83,58	0	83,75	23,19	2828,49
2013.06.25 09:32:35	14,9	14,9	0	−0,86	15,26	0	50,3	0	0	83,86	0	84,02	23,27	2828,49
2013.06.25 09:33:05	14,9	14,9	0	−0,98	15,38	0	50,29	0	0	83,16	0	83,33	23,07	2828,49
2013.06.25 09:33:35	14,9	14,9	0	−0,75	15,15	0	51,31	0	0	84,44	0	84,6	23,43	2828,49
2013.06.25 09:34:06	14,9	14,9	0	−0,23	14,63	0	50,45	0	0	83,01	0	83,18	23,03	2828,49
2013.06.25 09:34:36	14,9	14,9	0	−0,23	14,63	0	51,3	0	0	84,54	0	84,71	23,46	2828,49
2013.06.25 09:35:06	14,9	14,9	0	0	14,57	0	50,29	0	0	82,85	0	83,01	22,99	2828,49
2013.06.25 09:35:36	14,9	14,9	0	0,06	14,34	0	48,3	0	0	84,71	0	84,88	23,5	2828,49
2013.06.25 09:36:06	14,9	14,9	0	−1,03	15,44	0	53,65	0	0	83,07	0	83,23	23,05	2828,49
2013.06.25 09:36:36	14,9	14,9	0	−0,34	14,75	0	51,46	0	0	84,12	0	84,29	23,34	2828,49
2013.06.25 09:37:06	14,9	14,9	0	−0,75	15,15	0	52,8	0	0	83,43	0	83,6	23,15	2828,49
2013.06.25 09:37:36	14,9	14,9	0	0	10,9	0	41,47	0	0	84,02	0	84,18	23,31	2828,49
2013.06.25 09:38:06	14,9	14,9	0	0	10,9	0	45,47	0	0	84,29	0	84,45	23,39	2828,49
2013.06.25 09:38:36	14,9	14,9	0	0	10,78	0	45,31	0	0	83,27	0	83,43	23,1	2828,49
2013.06.25 09:39:06	14,9	14,9	0	0	11,07	0	45,31	0	0	84,86	0	85,02	23,54	2828,49
2013.06.25 09:39:36	14,9	14,9	0	0	11,19	0	45,31	0	0	83	0	83,17	23,03	2828,49

4.3.2 Variables that are calculated

The second step in the data processing is to determine variables that are calculated using mathematical formulae. These are equivalent circulation density and pore pressure gradient. The process of determining/calculating these parameters is discussed in section below.

The pore pressure gradient

Calculating x3 requires the values of pore pressure gradient at the given depth. Pore pressure at a given depth is as a result of compaction by weight of formation and water above it. This weight is carried by the solid matrix and the fluid that is contained inside the pores. The pressure exerted by the column of fluid within the pores is commonly referred to as the formation pressure or the pore pressure. The pore pressure increases with depth and density of the fluid within the pores, (Darley et al., 1988). The pore pressure gradient can be determined by well logging. The pore gradient for well MW-17 was determined from the temperature pressure (TP) profile measurements done after the well had been drilled. The TP measurements capture the pressure and temperature versus depth. The pressure and temperature were then used to determine the density of the fluid in the well from the X steam add-in macros prepared in Excel by Magnus Holmgren, 2007. This density, the measured pressure at the given depth and the wellhead pressure measurements were then used to determine the pore pressure gradient of the formation as shown below.

Pore pressure gradient was determined by assuming that the formation is hydraulically connected. The pressures in a hydraulically connected formation can be calculated based on the difference in the heights of the fluid columns (hydrostatic) below (Zhang, 2011) as shown in Equation 39:

TABLE 6: Measure data at rig-after initial processing

Date&Time	Hole Depth m	ROP min/m	WOB 10kN	RPM r/min	Flow In L/s
2013.06.25 09:16:04	14,9	0	0	50,84	23,22
2013.06.25 10:32:22	14,97	516,41	1,32	48,14	23,15
2013.06.25 10:33:52	14,97	516,41	1,21	48,3	23,46
2013.06.25 10:34:22	14,97	516,41	0,69	49,52	23,11
2013.06.25 10:34:52	14,97	516,41	0,06	49,65	23,34
2013.06.25 10:36:52	14,97	516,41	0,8	49,33	23,05
2013.06.25 10:37:22	14,97	516,41	0,17	49,5	23,46
2013.06.25 10:38:22	14,98	516,41	1,03	46,96	23,27
2013.06.25 10:39:22	14,98	516,41	1,32	47,11	23,11
2013.06.25 10:39:52	14,98	516,41	1,38	48,45	23,48
2013.06.25 10:40:52	14,98	516,41	1,32	49,82	23,43
2013.06.25 10:41:22	14,98	516,41	0,23	49,65	23,15
2013.06.25 10:41:52	14,98	516,41	0,06	49,97	23,27
2013.06.25 10:42:22	14,99	516,41	1,15	46,79	23,34
2013.06.25 10:42:52	14,99	516,41	0,06	49,82	23,22
2013.06.25 10:43:23	14,99	516,41	1,38	47,58	23,43
2013.06.25 10:43:53	14,99	516,41	0,34	49,11	23,19
2013.06.25 10:45:53	14,99	516,41	1,49	48,78	23,31
2013.06.25 10:46:23	14,99	516,41	0,63	49,1	23,22
2013.06.25 10:47:53	15	516,41	1,78	49,1	23,51
2013.06.25 10:48:53	15	516,41	1,09	46,64	23,51
2013.06.25 10:49:23	15	516,41	0,17	49,1	23,15
2013.06.25 10:52:53	15	516,41	0,29	49,34	23,22
2013.06.25 10:54:23	15,01	516,41	0,46	49,34	23,11
2013.06.25 10:54:53	15,01	516,41	0,17	49,82	23,46
2013.06.25 10:55:54	15,01	516,41	0,29	49,81	23,43
2013.06.25 10:56:24	15,01	516,41	1,44	48,29	23,08
2013.06.25 10:56:54	15,01	516,41	0,23	49,51	23,43
2013.06.25 10:57:54	15,02	516,41	0,46	50,13	23,19
2013.06.25 10:58:24	15,02	516,41	0,06	49,96	23,39
2013.06.25 10:58:54	15,02	516,41	0,57	52,15	23,15
2013.06.25 10:59:24	15,02	516,41	0,23	49,65	23,46
2013.06.25 10:59:54	15,02	516,41	0,17	50,43	23,19
2013.06.25 11:00:24	15,03	516,41	0,92	49,96	23,31
2013.06.25 11:01:24	15,03	516,41	0,8	49,49	23,11
2013.06.25 11:01:54	15,03	516,41	0,06	49,96	23,5
2013.06.25 11:04:24	15,05	516,41	0,69	50,12	23,46
2013.06.25 11:04:54	15,05	516,41	0,69	49,34	23,08
2013.06.25 11:05:24	15,05	516,41	0,8	49,81	23,46
2013.06.25 11:08:55	15,05	516,41	0,46	47,42	23,55
2013.06.25 11:09:55	15,06	516,41	0,06	50,28	23,34
2013.06.25 11:10:55	15,07	382,01	1,21	48,78	23,22
2013.06.25 11:11:25	15,07	382,01	0,69	49,65	23,47
2013.06.25 11:11:55	15,07	382,01	1,9	49,81	23,11
2013.06.25 11:12:25	15,07	382,01	0,23	49,96	23,55

$$P_p = P_l + \rho_f g(h_2 - h_1) \tag{39}$$

where P_p = Formation fluid pressure, Pa or psi at depth h_2;
P_l = Formation fluid pressure, Pa or psi at depth h_1;
ρ_f = Fluid density, kg/m^3;
g = Acceleration of gravity, m/s^2.

Since the pressures P_l has been measured in the entire well depth while doing the PT logging, the pore pressure at a desired depth is here determined by adding the term ρf g (h) where h is the depth at the point where the pressure is measured. Hence modifying Equation 39 to get pore pressure gradient with units N/L or lb/gal becomes:

$$P_{pg} = \frac{P_l}{1000D} + \frac{\rho_f g}{1000} \tag{40}$$

where P_{pg} = Pore pressure gradient, N/L.

Equivalent circulating density (ECD)
Equivalent circulating density represent the bottom hole pressure exerted on the formation that is being drilled presented in terms of equivalent density. ECD is the sum of the static density, the additional density increment due to the weight of drill cuttings contained in the annulus and the effect of pressure

drop along the annulus (Skalle, 2011). ECD takes into account the frictional loss due to circulation of the drilling fluid being pumped by the mud pumps. This is calculated using Equation 41 below (Lyons et al., 2012):

$$ECD = \frac{Annulus\ friction\ pressure\ loss}{1000\ h} + MW \tag{41}$$

where Annulus frictional pressure loss is in N/m^2;
ECD = Equivalent circulating density, N/Litre;
h = Depth, m;
MW = Mud weight, N/ Litre.

The annulus friction pressure loss is calculated as discussed in Section 3.3.1. The pore pressure gradient and ECD for well MW-17 have been plotted together as shown in Figure 11.

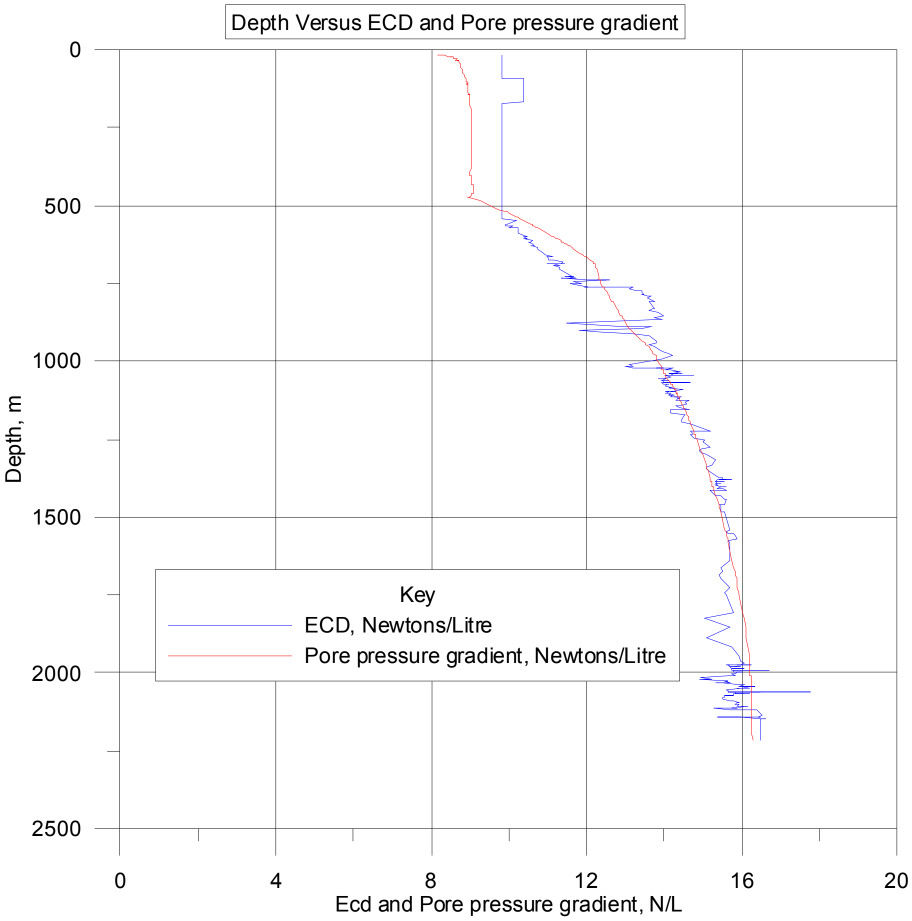

FIGURE 11: ECD and pore pressure gradient for well MW-17

4.3.3 Variables that needed special tests or measurements

The final step in the data analysis is to determine values of variables that need special tests or measurements. The values of these variables were not available and the values used were taken from past research work having similar properties. These variables are Threshold weigh on bit, the viscosity and yield strength of bentonite mud. This is discussed below how they were determined.

Threshold weight on bit

Threshold bit weight is the minimum weight applied on the rock being drilled at which the bit begins to drill. Below the threshold bit weight, no significant rate of penetration is realized. The relationship between ROP and WOB holding all other factors constant is as shown in Figure 12. There is no significant ROP realized until the threshold WOB is applied shown by point a. After applying the threshold WOB, there is rapid increase in ROP with moderate increase in WOB (section ab). A linear relationship between the ROP and WOB is observed for moderate WOB (section bc) and at higher values of WOB, subsequent increase in WOB only results in slight increase in ROP (section cd). In some cases, a decrease in ROP is observed at extremely high values of WOB as seen in section de. This behaviour is called bit floundering and is attributed to poor hole cleaning at the bottom of the hole due to high generation of cuttings (Bourgoyne et al., 1991)

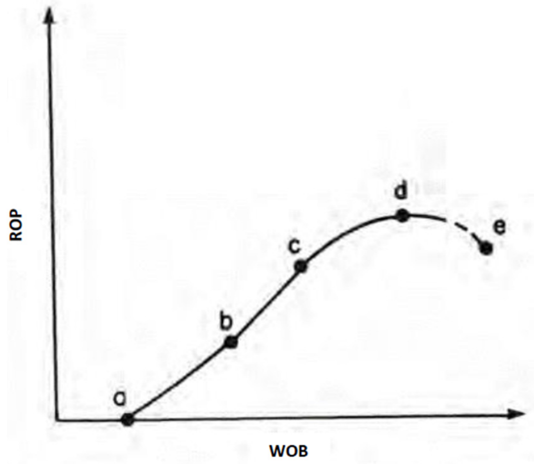

FIGURE 12: ROP versus WOB

While drilling well MW-17, the data used to generate the graph in Figure 12 (Bourgoyne et al., 1991) was not recorded as rig data. The threshold used in the model was determined from the general properties of the rocks being drilled. The threshold strength and hence the threshold weight on bit of the rocks in well MW-17 were estimated from studies carried out by Xiao et al., 2011 on compression tests of different samples of volcanic rocks as shown in Table 7.

TABLE 7: Values of Xiao´s study on compression test

Rock type	Sample	σ3 (Mpa)	σ1 (Mpa)	Orientation of failure plane φ (°)	Angle of internal friction θ (°)	Shear strength MPa
Trachyte	015-1	26.1	167.52	24.35	41.3	53.12188688
Trachyte	015-4	26.33	176	24.35	41.3	56.22085143
Trachyte	015-8	28.6	302.51	24.35	41.3	102.8893794
Trachyte	027-1	28.2	153.83	24.35	41.3	47.19065655
Trachyte	027-4	31.24	233.76	24.35	41.3	76.07300616
Tuff	028-2	26	93.82	31.57	26.86	30.25155764
Basalt	030-1	29.41	111.79	32.5	25	37.33081775

Equation 42 on rock failure mechanisms (Bourgoyne et al., 1991) was used to determine the shear strength of the rocks:

$$\tau = (\sigma_1 - \sigma_3)\sin 2\varphi \qquad (42)$$

where τ = Shear strength;
σ_1 = Compressional loading;
σ_3 = Confining pressure;
φ = Angle of internal friction.

The shear strength values of the various rocks from Table 7 were then used to determine the threshold bit weight for the different rock types using Figure 13 (Bourgoyne et al., 1991).

The minimum values of threshold were chosen from the samples to be used in the model. The resulting values of threshold bit weight per inch of diameter used in the modelling are as shown in Table 8.

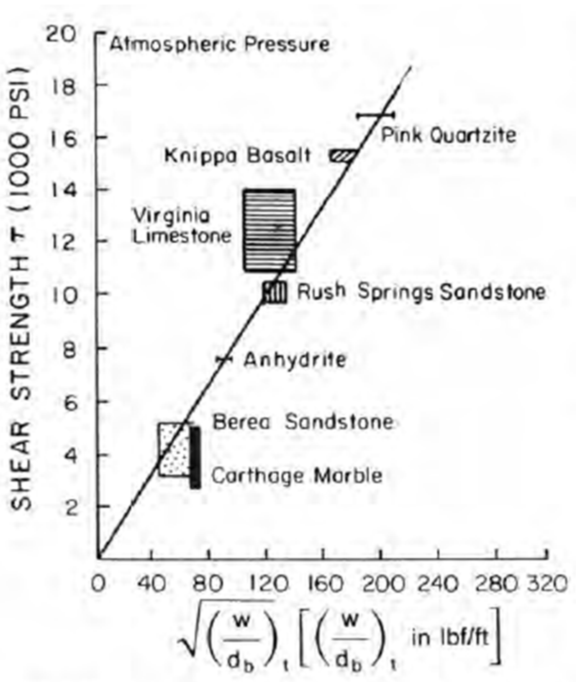

FIGURE 13: Relation between rock shear strength and threshold bit weight at atmospheric pressure

TABLE 8: Threshold shear strength

Common rock type	Shear strength, MPa	Shear strength, 1000 PSI	Threshold weight/ft	Threshold strength 1000 lb/ft	Threshold strength 1000 lb/in
Trachyte	47.2	6.85	85.0	7.23	0.60
Intrusive/syenite	3.204	0.46	5.0	0.03	0.002
Tuff	30.2	4.38	50.0	2.5	0.21

Viscosity, density and Nozzle diameter for determining the Reynolds number function
In drilling well MW-17 no bit nozzles were used hence the nozzle diameter was taken as the diameter of the nozzle boss of the bits used in drilling the well.

Three types of drilling fluids were used in the data analysis, these are: water, aerated water and water based Wyoming bentonite drilling mud. The properties of water were determined from the X Steam macros in Excel prepared by Magnus Holmgren, 2007 that's prepared from steam tables.

The properties of the bentonite mud used was taken from field measurements and from typical clay yield curves by Darley et al., 1988 as shown in Figure 14 (Darley et al., 1988) below.

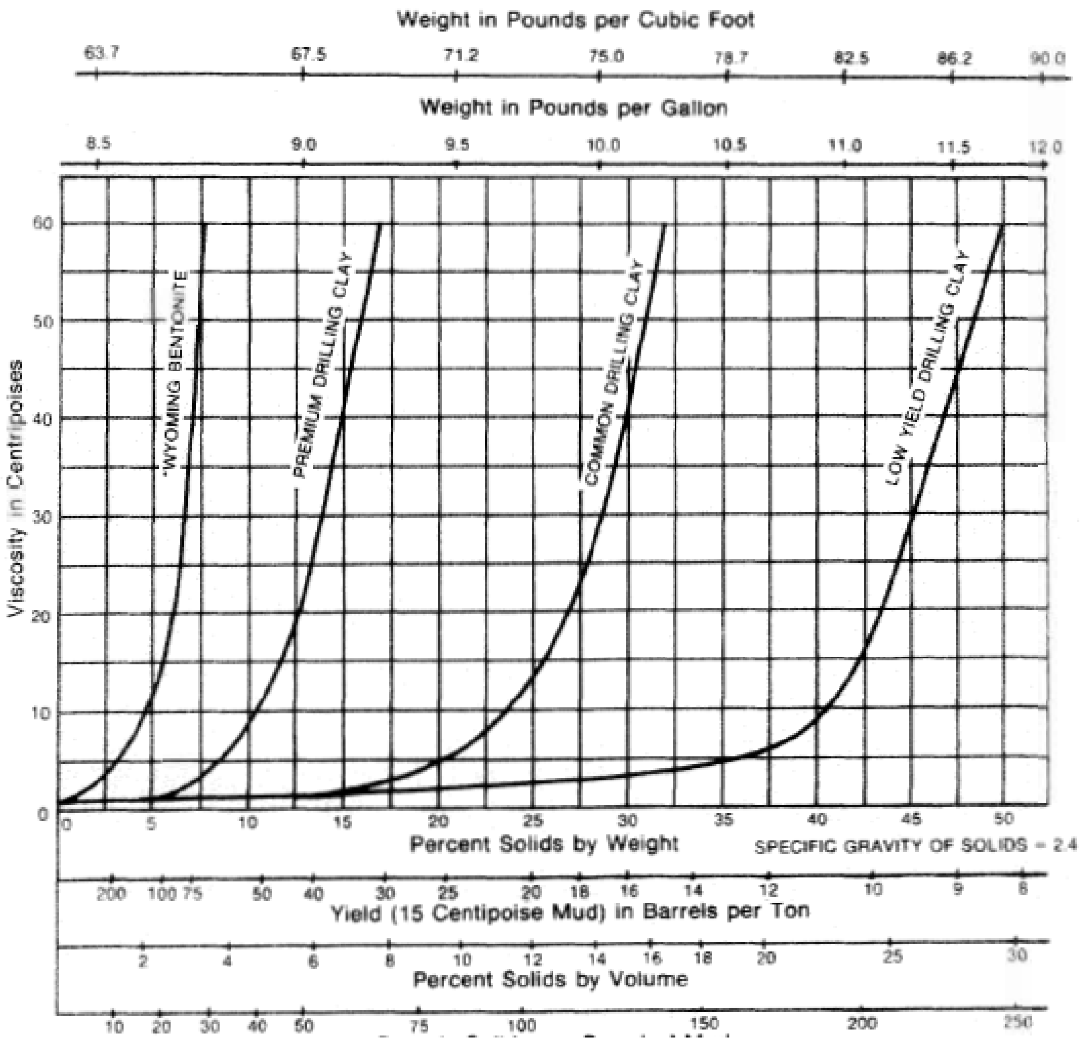

FIGURE 14: Typical clay yield curves

4.4 Case study: Modelling well MW-17 for Rop

As discussed in section 1.3 on results of background research, Well MW-17 was divided into 21 sections by following the lithostratigraphy and the casing size of each of the sections as shown in Figure 15 (MW-17 Completion report, 2013). Variables for each section of the well were determined separately and modelled separately. MatLab code was developed for each of these sections to determine regression coefficients.

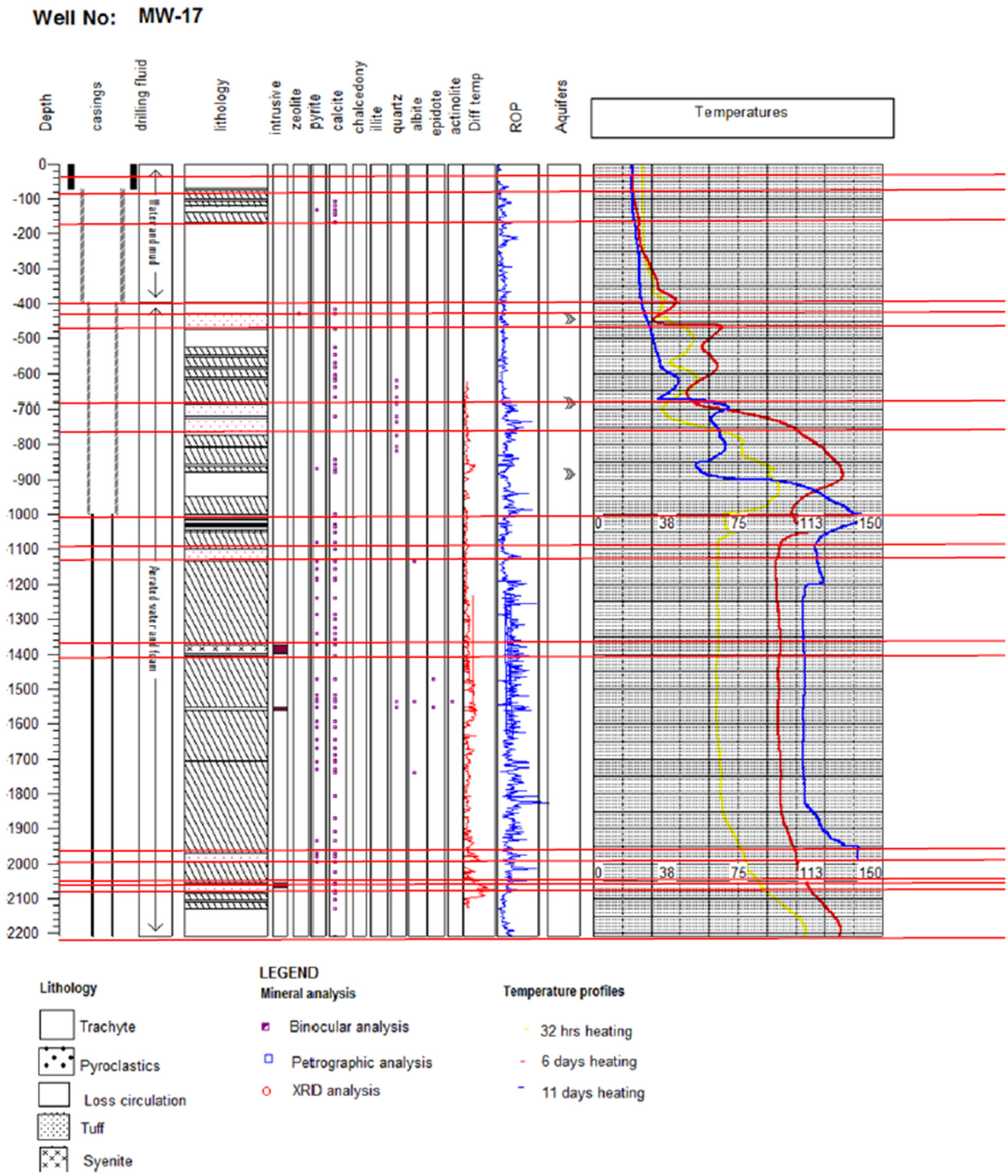

FIGURE 15: Subdivision of well MW-17 into 21 sections

4.5 Multiple linear regression

Many applications of regression analysis involve situations in which there are more than one regressor variable. A regression model that contains more than one regressor variable is called a multiple regression model. Multiple linear regression models are often used as approximating functions. That is, the true functional relationship between the dependent and the independent variables is unknown, but over certain ranges of the independent variables the linear regression model is an adequate approximation (Montgomery et al., 2003). In this drilling model, there are eight regressors a_1 to a_8.

Using data from the field, the 'a' constants in Equation 43 are determined through multiple regression. If Excel is to be used to do the regression, the procedure for finding the values a_1 to a_8 is as shown below. Eight equations are generated which care then solved to find the constants (Eren, 2010).

Taking logarithms on both sides of Equation 1 yields:

$$ln\left(\frac{dD}{dt}\right) = \left(a_1 + \sum_{j=2}^{8} a_j x_j\right) \quad (43)$$

Equation 43 can be checked for validity in a given formation type at each depth at which data have been collected. If we define a residual error i^th^ data point, r_i, by:

$$r_i = a_1 + \sum_{j=2}^{8} a_j x_j \quad (44)$$

Then we select a_1 to a_8 so that for n data points, the sum of the squares of the residuals $\sum_{i=1}^{n} r_i^2$ is a minimum.

Using calculus:

$$\frac{d\sum_{i=1}^{n} r_i^2}{da_j} = \sum_{i=1}^{n} 2r_i \frac{dr_i}{da_j} = \sum_{i=1}^{n} 2r_i x_j = 0 \quad (45)$$

For j=1, 2, 3…8. The constants can be simultaneously obtained by solving the system of equations obtained by expanding Equations 43,44 and 45. Thus:

$$a_1 n + a_2 \sum x_2 + a_3 \sum x_3 + \cdots a_8 \sum x_8 = \sum ln\frac{dD}{dt} \quad \text{(i)}$$

$$a_1 \sum x_2 + a_2 \sum x_2^2 + a_3 \sum x_2 x_3 + \cdots a_8 \sum x_2 x_8 = \sum x_2 ln\frac{dD}{dt} \quad \text{(ii)}$$

$$\cdots$$

$$\cdots$$

$$a_1 \sum x_8 + a_2 \sum x_8\ x_2 + a_3 \sum x_8 x_3 + \cdots a_8 \sum x_8^2 = \sum x_8 ln\frac{dD}{dt} \quad \text{(viii)}$$

The ´x´ values are determined by applying Equations 2-8 using the data that has been acquired while drilling a well. The ´a´ values are determined from Equations (i) – (viii) using multiple regression technique. A matrix is then generated from the eight equations which can be solved using Excel.

Alternatively, a high level technical computing language such as MATLAB, EEE, Python etc. can be used to do the regression and hence determine the 'a' constants. In this case there will be no need to generate the eight equations but instead a code is written to do the regression and determine the constants. In this thesis, a combination of Excel and MATLAB has been used to do the data analysis. Excel has been used to do the initial data processing after which a MATLAB code was written to do the multiple linear regression to determine the values of the ´a ´constants. The MatLab code for the sections is shown in Appendix I.

5. RESULTS AND DISCUSSION

The results of the modelling and discussion of the results is given for each section. A few figures are shown below for each section of the well. The rest of the figures which show similar results are shown in Appendices.

5.1 The ´a´ Coefficients

The modelling the ROP has been made by using the ´a_i´ values. Table 9 shows ´a_i´ values which are the result of the regression analysis for the various sections of the well. The ´a_i´ values were used to calculate the modelled ROP and the result is shown in the figures show below.

TABLE 9: Values of ´a_i´ in each regression section

Depth, m	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
0-33.83	-1403.260	0.135	-4.406	1.089	0.000	-0.801	0	-0.079
33.83-82.57	-1539.95	0.16	1.29	-0.53	0.00	-2.10	0	0.04
82.57-120.95	-127.378	0.013	-0.089	-0.007	0.015	5.417	0	0.112
120.95-169.19	2039.05	-0.21	-1.79	0.40	0.04	0.70	0	-7.80
169.19-398	394.9040	-0.0378	0.3255	0.0026	-0.0225	0.7506	0	-0.1187
398-409	50823.43	-4.15	159.47	-17.15	0.27	-3.97	0	-0.49
409-428	-5567.40	0.44	-16.93	1.67	0.34	-3.62	0	0.14
428-472	5591.59	-0.46	16.51	-1.69	0.03	3.00	0	0.58
472-684	56.1660	-0.0070	-0.0106	0.0003	0.1699	-6.7634	0	0.0733
684-772.97	1.9626	0.0017	0.0020	-0.0017	-0.4447	-9.1884	0	-1.5676
772.97-1010	-55.34238	0.00697	0.01438	0.00005	0.04089	0.24787	0	0.01742
1010-1098	-43.2378	0.0080	0.0153	-0.0013	-0.1470	-1.4832	0	-2.0303
1098-1135.95	291.45518	-0.04004	-0.05519	0.00121	-0.46741	-1.67306	0	1.28241
1135.95-1375.37	161.6698	-0.0246	-0.0563	0.0024	-0.3970	-0.5295	0	4.4247
1375.37-1410.7	109.200	-0.010	-0.008	-0.002	0.182	1.762	0	-3.938
1410.7-1970	28.6669	-0.0027	-0.0071	0.0001	-0.2407	3.5067	0	-0.0631
1970-1996.69	504.4515	-0.0610	-0.1495	0.0006	-0.1711	-2.5533	0	1.5017
1996.69-2057.52	-335.5602	0.0280	0.1194	-0.0003	0.0911	-0.2625	0	-0.5695
2057.52--2060.71	280.3454	0.0438	-0.1892	-0.0008	-0.0461	3.4972	0	-1.5190
2060.71-2082.95	-371.2043	0.0371	0.1137	-0.0002	0.5137	-25.3201	0	-0.5001
2082.95-2218	-77.3583	0.0073	0.0196	0.0004	-0.6479	-3.9719	0	1.0930

The constant a_1 gives the formation strength and other factors that are not modelled such as effect of drilled cuttings etc. The a_1 constant which is for varied considerably for the entire section of the well. The value of a_1, ranged from -5500 to 50000. The magnitude of the constant is bigger at the top of the hole and much smaller at the bottom section.

The coefficient a_2 represents the compaction effect on rate of penetration. Magnitude of a_2 ranged from -4 to 0.46. Majority of the values are in the range of hundredths and thousandths. This implies that compaction effect is not dominant in the field. This is supported by drillability of the formations improving with depth.

The a_3 constant shows the effect of under compaction due to formations that have abnormally high pressures. The values varied from -4.4 to 159. Majority of values are in the range of hundredths. The value 159 appears as an outlier.

The constant a_4 which gives the effect of pressure differential at the bottom of the hole ranges from -17 to 1 where mud and water was used (0-500 m) in drilling and from -0.0017 to 0.0024 where aerated water was used (500 to 2218).

The constant a_5 that gives the effect of bit weight on bit and bit diameter varies down the hole because WOB is a controllable parameter. The surface section has magnitude of this value equal to zero (because the WOB applied is less than threshold weight) and generally increasing with depth.

The a_6 that gives the effect of rotary speed greatly varies from the surface to the bottom. Rotary speed is a controllable parameter.

The a_7 constant that models the effect of tooth wear is zero in his modelling. This is because tungsten carbide insert tooth bits were used in drilling well MW-17. This is because ROP does not vary significantly with tooth wear of these kind of bits (Bourgoyne et al., 1991).

The a_8 coefficient shows effect of the hydraulics function. Majority of these values are in the range value of tenths.

5.2 Results of modelling for the surface hole

The values of ´a_is´ (Table 9) from multiple linear regression were used to model the rate of penetration for each section of the well. The results of the modelling are shown in the following graphs.

5.2.1 Modelled versus measured values for the entire well

Figure 16 below shows the result of the modelled rate of penetration and measured rate of penetration for the whole well. The result from each section was combined to give the overall picture of the model. The result of the model follows closely the measured values and trend.

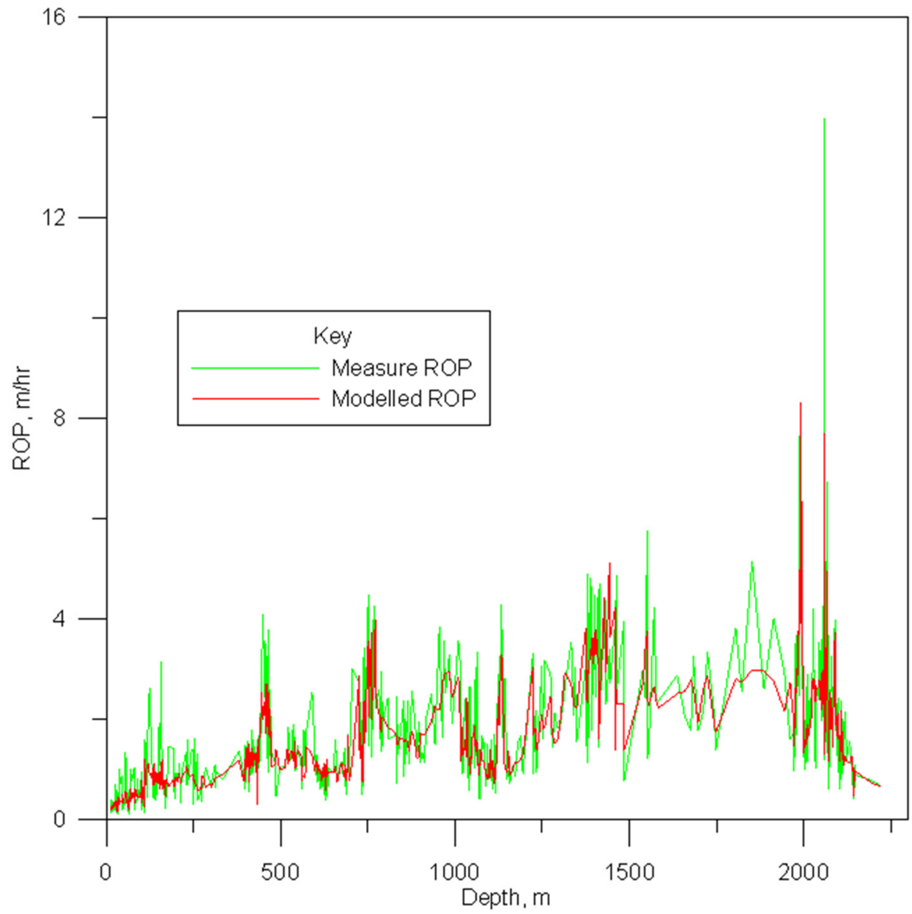

FIGURE 16: Result of the modelled versus measured rate of penetration

5.2.2 Modelled versus measured values for the surface hole

Figure 17 shows the result of modelling the rate of penetration compared with the measured rate of penetration. The predicted rate of penetration is below the measure rate of penetration. Although the model tends to follow the general trend of the measured value, a perfect fit was not possible. This may be attributed to the excessive vibrations and abrasive formation encountered on the surface hole. The applied weight on bit was below the threshold value as a result of the vibrations and this may have resulted in not getting a perfect fit from the model. Application of sufficient weight on bit on the formation above the threshold value is required. The available alternative is the use of Hammer bits. (DTH air hammers) can be used in this section and rotary drilling employed at deeper sections of the well.

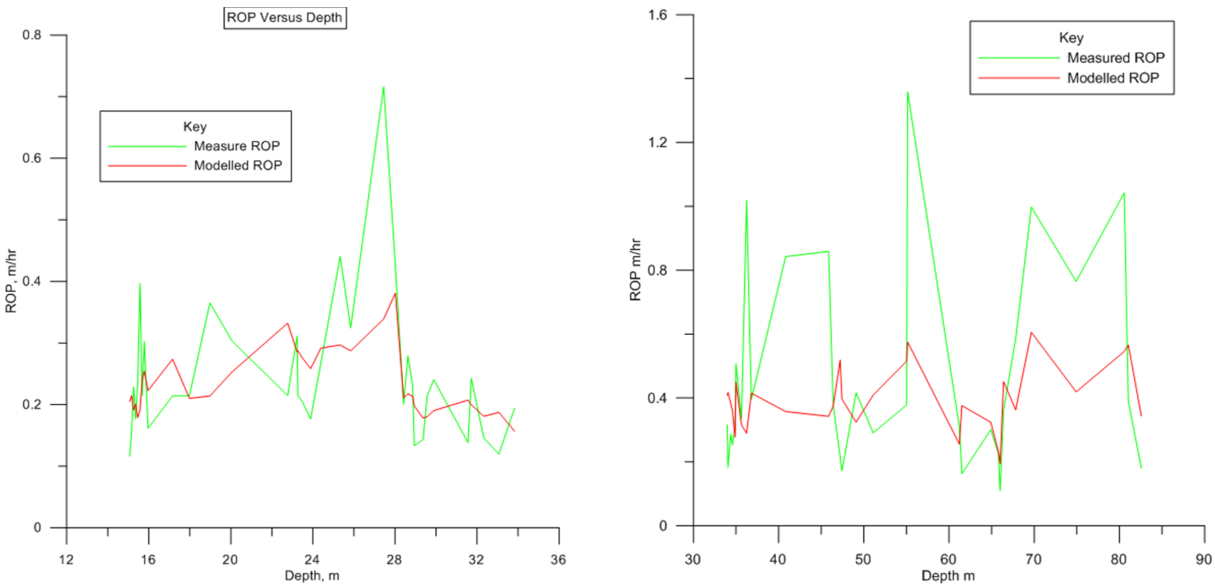

FIGURE 17: Modelled and measured ROP for the surface hole section

5.3 Results of modelling for the intermediate hole

Figure 18 shows the result of modelling the intermediate hole. The model shows a slight improvement compared to the one for the surface hole. This section of the well has a better drillability compared to the surface hole. However, in many instances, the weight on bit was below the threshold value as can be seen in the results for optimization. The improvements needed in this section is applying sufficient weight on bit consistently to improve the penetration rate. More figures for his section are given in Appendix II.

5.4 Results of modelling for the production hole

Figure 19 shows the result of the model for the production. The model follows the trend of the measured drilling rate and in some points has a fairly good fit. The model has improved compared to the intermediate hole. The weigh on bit applied on the formation in this section was above the threshold value most of sections although there are instances where it was below the threshold value. This section of the well has a good drillability.

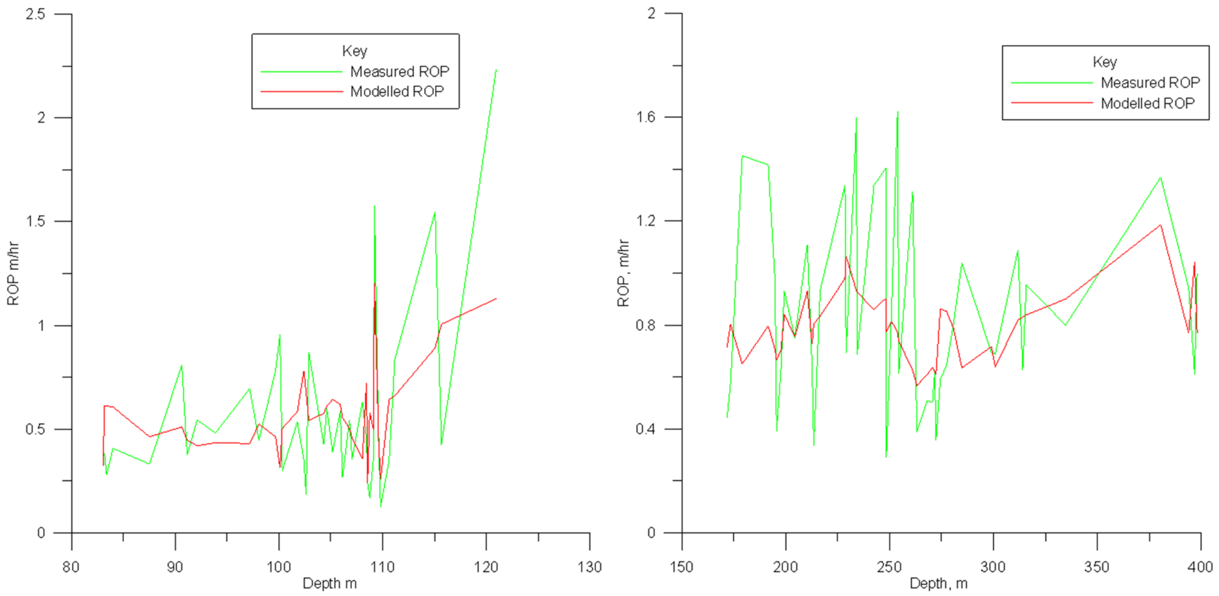

FIGURE 18: Modelled and measured ROP for the intermediate hole section

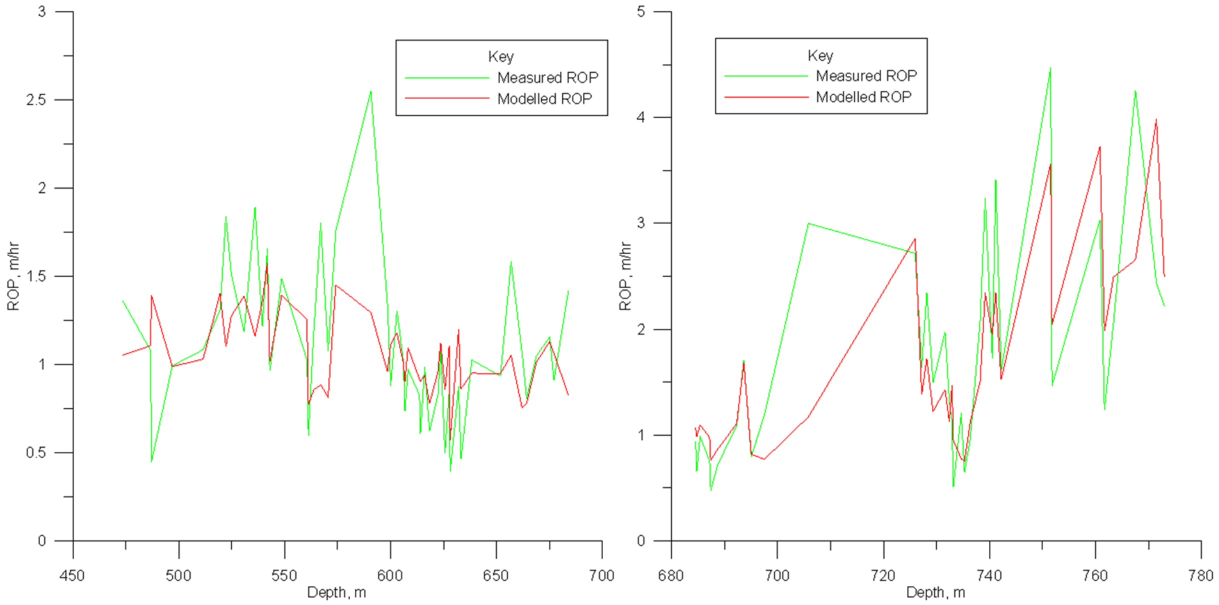

FIGURE 19: Modelled and measured ROP for the production hole section

5.5 Results of modelling for the open hole

Figure 20 shows the result of modelling the rate of penetration for the open hole. Compared with the other sections the model for this section has a better trend and fits fairly well in some points. The weight on bit in this section was applied above the threshold value. This section has the best drillability compared to the other sections of the well. The result for the rest of the sections is shown in Appendix II.

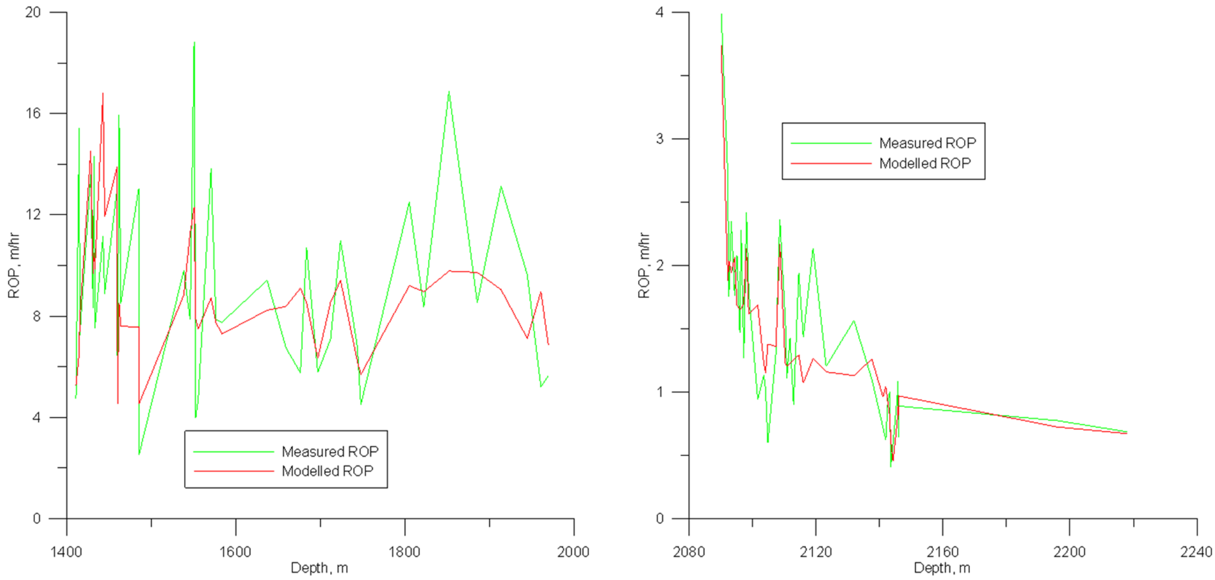

FIGURE 20: Modelled and measured ROP for the open hole section

5.6 Sensitivity analysis

The easily controllable parameters; WOB and RPM, were used to test the sensitivity on the ROP penetration by increasing and decreasing the parameters, one at a time, by 30% while holding the other parameters constant. Figures 22 to 27 below show the result of the sensitivity analysis. The sensitivity of ROP to changes in WOB and RPM was done by increasing and decreasing the WOB and RPM by 30% and the results are as discussed below.

Normally it is expected that ROP and RPM have a direct relation and thus increasing RPM should lead to an increase in ROP. Bourgoyne et al., 1991 stated that penetration rate increases linearly with rotary speed at low values of rotary speed as shown in Figure 21. The effect diminishes at higher rotary speed due to ineffective hole cleaning.

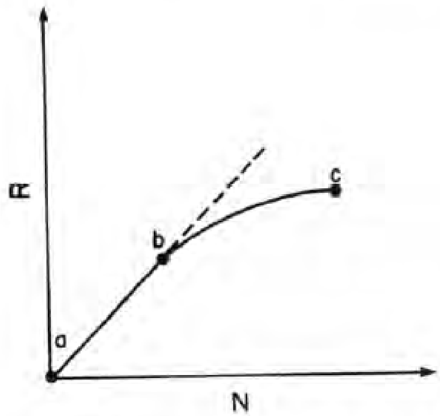

FIGURE 21: Rate of penetration (R) versus rotary speed (N)

In the same way increasing weight on bit is expected to lead to increase in rate of penetration as discussed under Figure 12.

5.6.1 Surface hole

By increasing the RPM by 30%, the model unexpectedly responded by a decrease in ROP. This is an abnormal response that may have been picked by the model as a result of applications of drilling parameters by the operator in a way that is not consistent.

In Figure 22 increase in rotary speed leads to a decrease in ROP. Analysis of the data showed a negative correlation of -0.27 between the RPM and ROP for this section. The drilling history recorded excessive vibration when increasing WOB and RPM to the point that it was impossible to make advances in depth hence decrease in ROP (Menengai well completion reports). This may have forced the operator to apply low RPM that led to Increase in ROP.

Increasing or decreasing WOB did not have an effect on ROP. This was because the weight on bit (WOB) used was so low that it didn't reach the threshold value for the model to respond in changing the ROP. Thus RPM had a greater effect on ROP than WOB for the surface section.

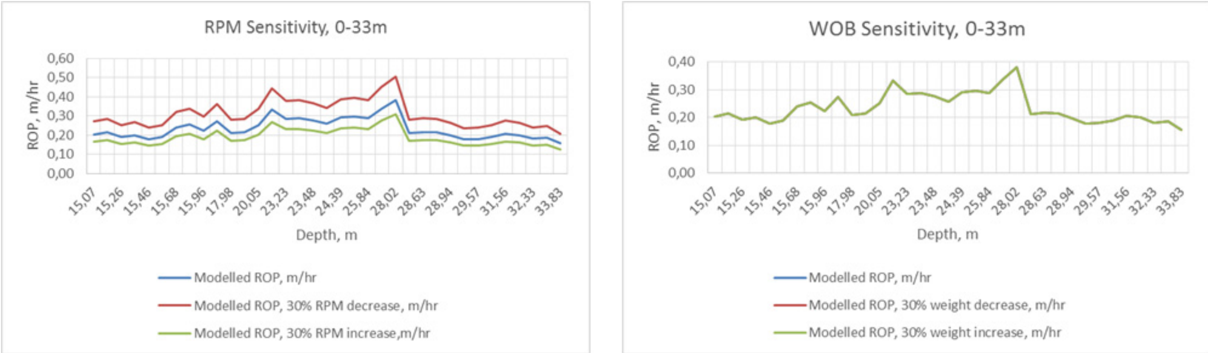

FIGURE 22: Sensitivity of ROP on WOB and RPM for the surface hole

5.6.2 Intermediate hole

In this section, increasing RPM led to a direct increase in ROP. Decreasing RPM on the other hand led to a direct decrease in ROP as seen in Figure 23. Changing WOB had little effect on ROP. This is because the WOB used was close to the threshold weight and in some cases below the threshold weight (Figure 23). The rest of the figures for this section are shown in Appendix II

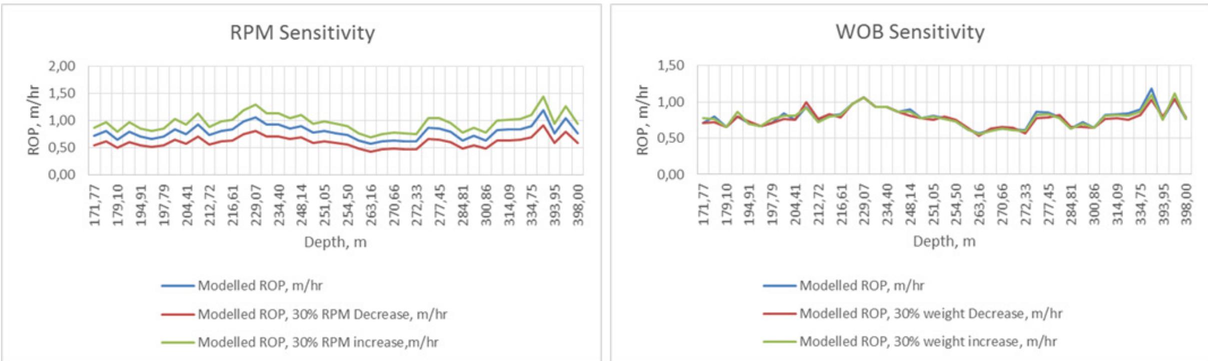

FIGURE 23: Sensitivity of ROP on WOB and RPM for the intermediate hole

5.6.3 Production hole

In this section (684-772 m), as seen in Figure 24, there is an indirect relationship between RPM, WOB and ROP. The ROP is very sensitive to changes in RPM. The data collected shows that the correlation between RPM and ROP is -0.4. The drilling history shows there was a fault with the torque sensor and the operator applied RPM and WOB reservedly when drilling this section (MW-17 well completion report, 2013). This section is composed of Tuff which is very soft and reducing WOB and RPM from previous high values still leads to an increase in ROP.

FIGURE 24: Sensitivity of ROP on WOB and RPM for the production hole

In section 772-1010 m (Figure 25), there is a direct relationship between RPM and ROP. Change in WOB had insignificant effect on the ROP this is because it is seen in Section 5.7.3 that the weight applied was mostly below the threshold weight. The rest of the Figures are in Appendix III.

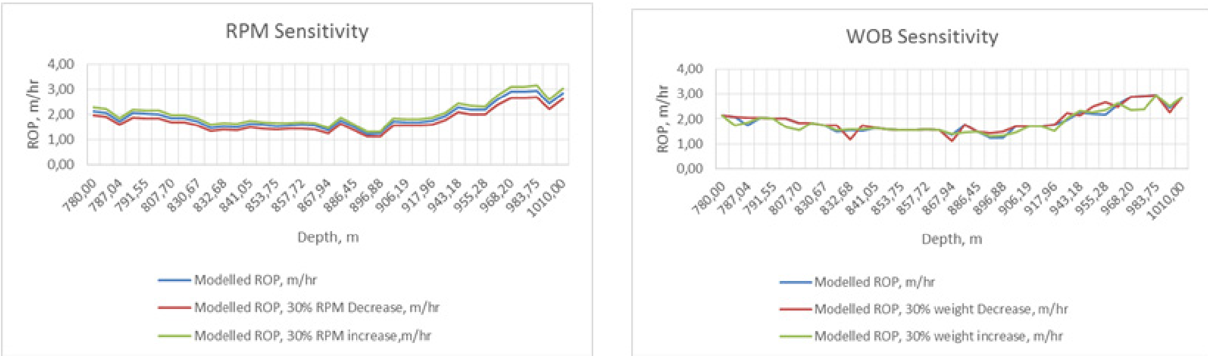

FIGURE 25: Sensitivity of ROP on WOB and RPM for the production hole

5.6.4 Open hole

The section 1375-1410 m, shows increasing WOB and RPM leading to a direct increase in ROP with RPM having a greater effect on the ROP than WOB as seen in Figure 26. In section 1410-1970 m, change in RPM leads to a direct change in ROP. A change in WOB leads to an indirect change in ROP. The correlation between measured WOB and measured ROP for this section is negative hence the model picked the indirect relationship as seen in Figure 27. This is because of the operator's application of parameters in a controlled manner since this section of the hole is prone to cause a stuck drill string. The rotary speed as a bigger effect on ROP for both cases in Figure 26 and 27.

FIGURE 26: Sensitivity of ROP on WOB and RPM for the production hole

FIGURE 27: Sensitivity of ROP on WOB and RPM for the production hole

5.7 Results from optimization

The Equations 40 to 44 using data for well MW-17 were used to optimize WOB and RPM for each section of the well. Results for each section are shown below. A few of the graphs are shown here for discussion. The rest of the graphs have similar results and are shown in Appendix IV.

5.7.1 Optimization results for the surface hole

Results of optimization of RPM and WOB on the surface section of the hole shows that the RPM is higher than the optimum value and WOB is below the optimum value. The maximum WOB is given by the manufacturer on the bits data sheet. Where the WOB applied is below threshold, optimizing WOB results to an optimum WOB equal to the threshold value (Figure 28).

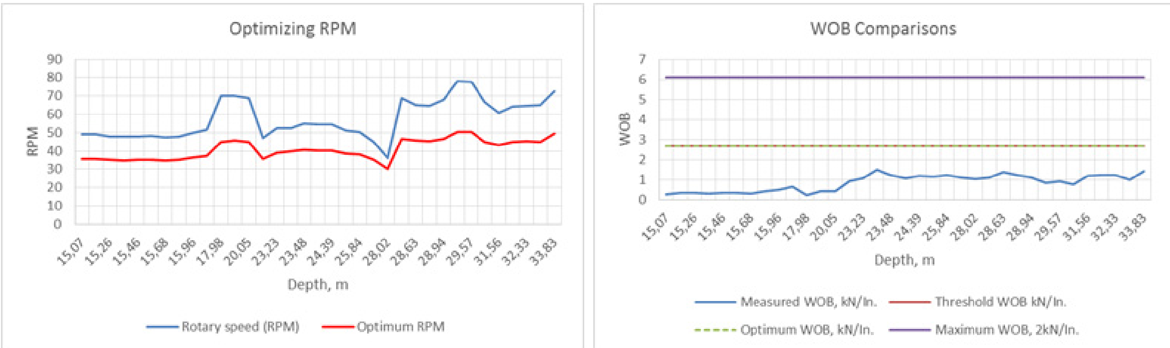

FIGURE 28: Optimized RPM and WOB, 0-33 m

5.7.2 Optimization results for the intermediate hole

In the intermediate hole, the RPM is very close to the optimum value as seen in Figures 29 and 30. The WOB is still falling below the threshold weight at some points.

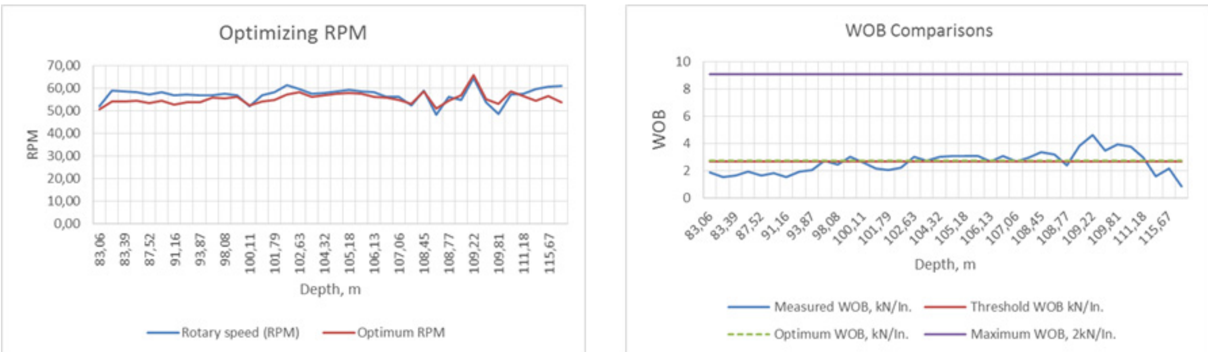

FIGURE 29: Optimized RPM and WOB, 82-120 m

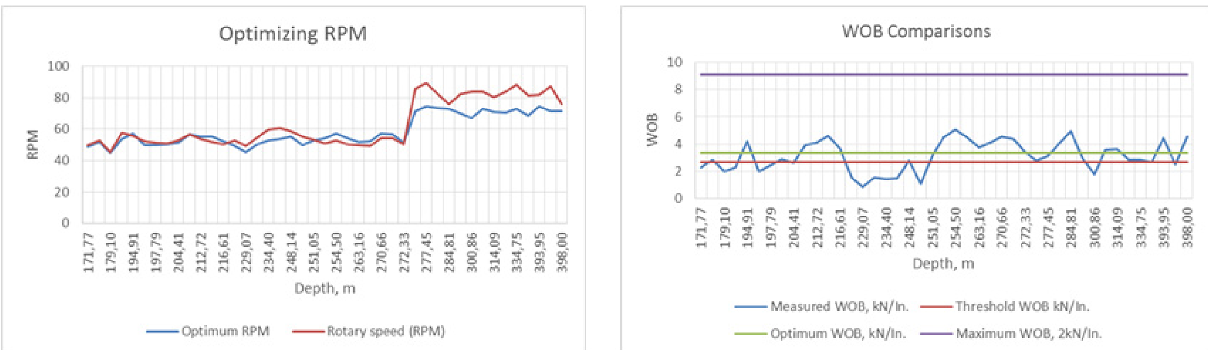

FIGURE 30: Optimized RPM and WOB, 169-398 m

5.7.3 Optimization results for the Production hole

In the production hole section, at 684-772 m the RPM is within the optimum limit as shown in Figure 31. The WOB is also within the optimum weight and above the threshold. At 772-1010 m (Figure 32), The RPM is above the optimum range and the WOB is below the optimum weight and within the threshold region. The parameters need to be changed to match the optimum values.

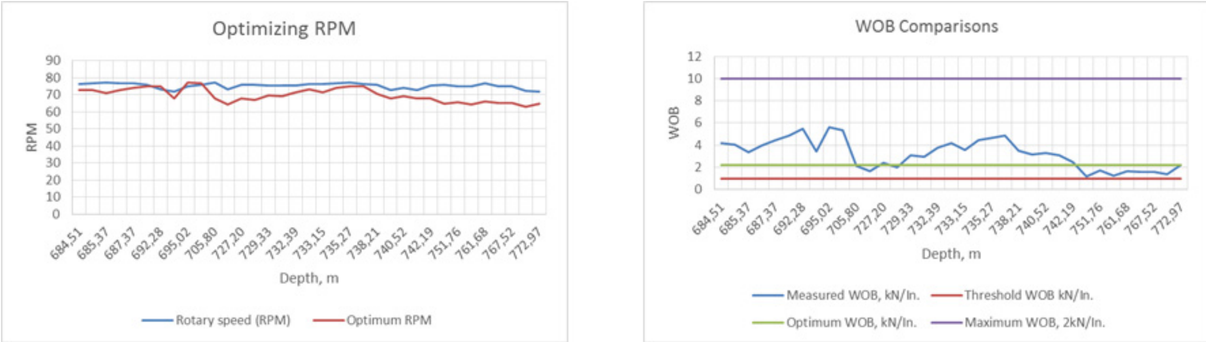

FIGURE 31: Optimized RPM and WOB, 684-772 m

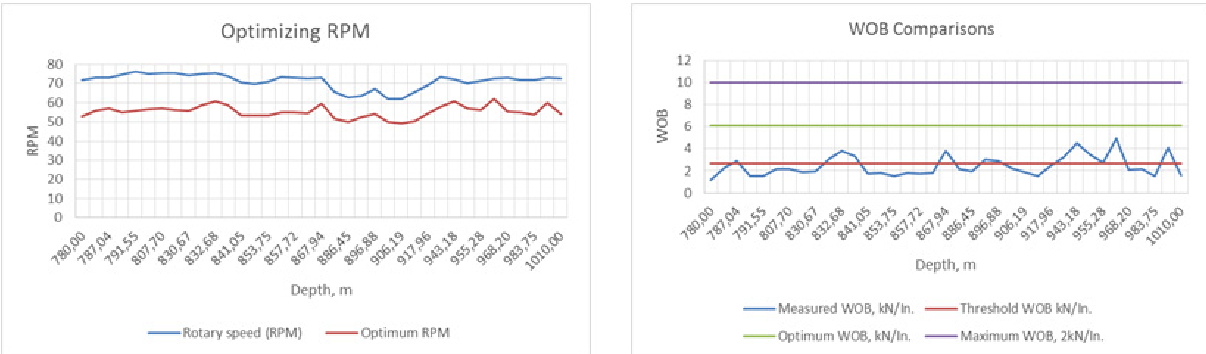

FIGURE 32: Optimized RPM and WOB, 772-1010 m

5.7.4 Optimization results for the open hole

In the open hole (1010-2218 m), the RPM is mostly below the optimum range but the WOB is above the threshold value all through (except for very insignificant portions) but within the optimum value of WOB. The result of optimization of rotary speed and WOB is shown in Figures 33, 34 and 35.

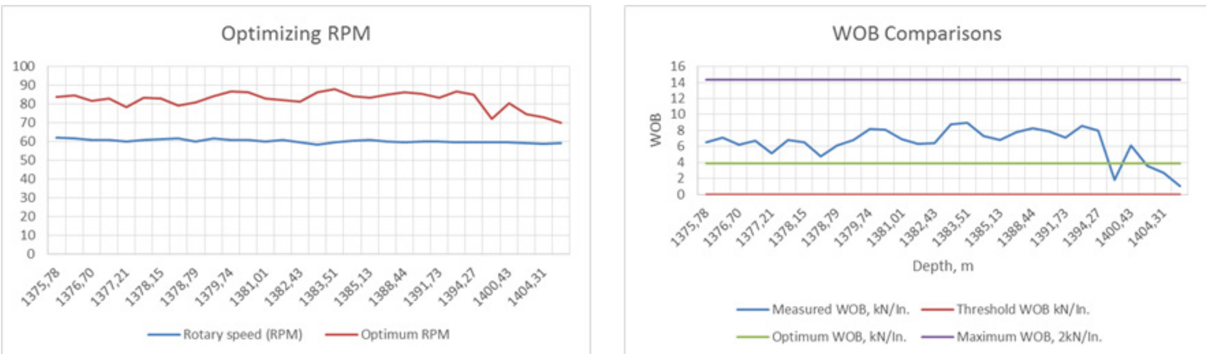

FIGURE 33: Optimized RPM and WOB, 1375-1410 m

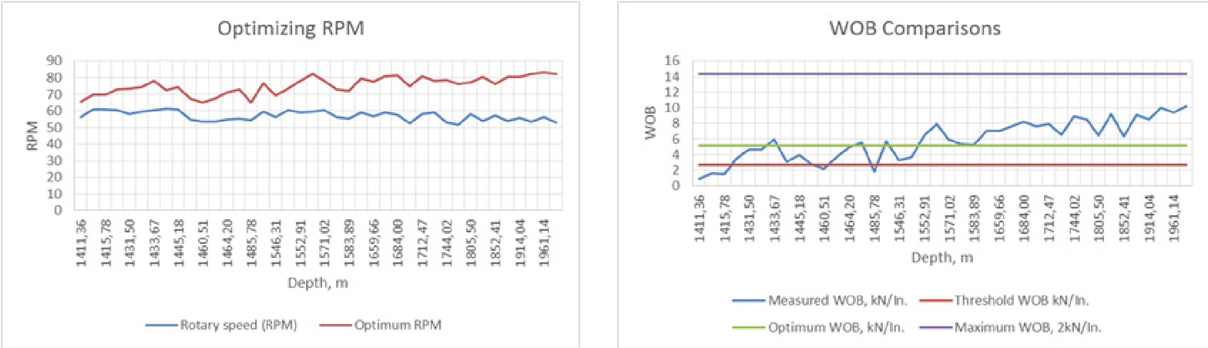

FIGURE 34: Optimized RPM and WOB 1410-1970 m

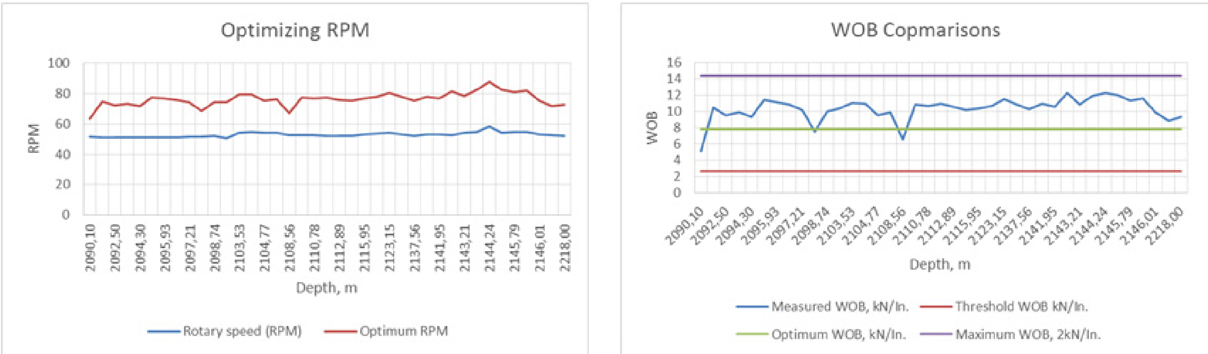

FIGURE 35: Optimized RPM and WOB, 2082-2218 m

5.8 Recommendations

In modelling the ROP some parameters had to be used from cited references as no data was available from well MW-17 such as the threshold weight, the formation abrasiveness and the pore gradient. It is recommended that drill off tests be done to determine at each change of formation type the threshold value of the weights. Detailed used bit records need to be kept and the conditions of bit accurately recorded to help in future research and studies.

Further study of other wells need to be done to compare and improve the values of the regression constants for the different formations. This will give a better understanding of the field and hence result to a more accurate application of the optimization tool to improve drilling performance of the field.

The WOB per inch of bit diameter for the surface and intermediate holes is below the threshold values. This weight the WOB/Inch ratio can be made to be greater than the threshold Weight per Inch. Alternatively, Hammer bits (DTH air hammers) can be used in this section and rotary drilling employed at deeper sections of the well.

6. CONCLUSION

The parameters from the multiple linear regression for the geothermal well differ slightly in some regression constants and greatly in other regression constants when compared with regression parameters from oil wells. This is because of slight differences in the drilling approach and drilling fluid designs used when drilling the two types of wells. The formations also differ greatly in that in the geothermal wells, the formation is made up of different types of rocks which may be greatly altered due to high temperatures encountered whereas the oil fields have more homogeneous formations.

For a more accurate modelling to be done, good data needs to be used, hence proper data acquisition and monitoring systems need to be used on the rigs. A good model will lead to improved determination of the best parameters to be used which will in turn lead to improvement in drilling performance.

The modelling of well MW-17 points to some changes that should be considered in the main parameters while drilling. Sufficient WOB needs to be applied above the threshold weight to ensure efficient cutting of the formation by the bit. There were many sections of the well where the WOB was insufficient.

From the optimization studies, the RPM at the open hole is always below the optimum value. Determining the appropriate RPM needs to be done by modelling using data from past drilled wells. A significant improvement in performance can achieved by this.

Since modelling in this thesis used only data from one well, data from other wells in the field need to be analysed to ascertain the best parameters to be employed in the field. Also a detailed study and modelling needs to done on the hydraulics optimization which was not done in this thesis.

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APPENDIX I: MatLab code for each section

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 0-33.83m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,1,'O2:O36');% h is the depth
gp = xlsread(filename,1,'V2:V36');%gp is the pore gradient of the formation
Ecd = xlsread(filename,1,'U2:U36'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,1,'Q2:Q36'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1; %is the constant for changing the percentages to check sensitivity
N = xlsread(filename,1,'R2:R36'); %Revolutions per minute
Tw = xlsread(filename,1,'S2:S36'); %Tooth wear
Re = xlsread(filename,1,'T2:T36');%Reynolds number function
ROP1 = xlsread(filename,1,'P2:P36'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 =  -1.40325973336121e+003;
a2 =  135.121940369695e-003;
a3 =  -4.40579515633519e+000;
a4 =  1.08940327924393e+000;
a5 = 0.00000000000000e+000;
a6 =  -800.661406192430e-003;
a7 = 0.00000000000000e+000;
a8 = -78.5775872462370e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP;
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 33.83m-82,57m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,2,'O2:O31');% h is the depth
gp = xlsread(filename,2,'V2:V31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,2,'U2:U31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,2,'Q2:Q31'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,2,'R2:R31'); %Revolutions per minute
Tw = xlsread(filename,2,'S2:S31'); %Tooth wear
Re = xlsread(filename,2,'T2:T31');%Reynolds number function
ROP1 = xlsread(filename,2,'P2:P31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
```

```
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;


a1 = -1.53995317632606e+003;
a2 = 155.306407496214e-003;
a3 = 1.29048476416776e+000;
a4 = -534.286553001076e-003;
a5 = 0.00000000000000e+000;
a6 =  -2.09600414438587e+000;
a7 = 0.00000000000000e+000;
a8 = 44.4724404138563e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled
ROP
%and other parameters for well MW-17 from 82.57-120.95m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,3,'O2:O39');% h is the depth
gp = xlsread(filename,3,'V2:V39');%gp is the pore gradient of the formation
Ecd = xlsread(filename,3,'U2:U39'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,3,'Q2:Q39'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,3,'R2:R39'); %Revolutions per minute
Tw = xlsread(filename,3,'S2:S39'); %Tooth wear
Re = xlsread(filename,3,'T2:T39');%Reynolds number function
ROP1 = xlsread(filename,3,'P2:P39'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = -127.377841924042e+000;
a2 = 12.5157316834615e-003;
a3 = -88.8589969796171e-003;
a4 = -7.34956480691240e-003;
a5 = 14.5435873375252e-003;
a6 =  5.41743192854737e+000;
a7 = 0.00000000000000e+000;
a8 = 111.593607233643e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 120.95-169.19m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,4,'O2:O33');% h is the depth
gp = xlsread(filename,4,'V2:V33');%gp is the pore gradient of the formation
Ecd = xlsread(filename,4,'U2:U33'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,4,'Q2:Q33'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,4,'R2:R33'); %Revolutions per minute
```

```
Tw = xlsread(filename,4,'S2:S33'); %Tooth wear
Re = xlsread(filename,4,'T2:T33');%Reynolds number function
ROP1 = xlsread(filename,4,'P2:P33'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;


a1 = 2.03904822114648e+003;
a2 = -207.889269692213e-003;
a3 = -1.79119276333800e+000;
a4 = 403.649560896437e-003;
a5 = 36.5048668223373e-003;
a6 =  704.570027231388e-003;
a7 = 0.00000000000000e+000;
a8 = -7.79741222611677e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 169.19-398m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,5,'O2:O44');% h is the depth
gp = xlsread(filename,5,'V2:V44');%gp is the pore gradient of the formation
Ecd = xlsread(filename,5,'U2:U44'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,5,'Q2:Q44'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,5,'R2:R44'); %Revolutions per minute
Tw = xlsread(filename,5,'S2:S44'); %Tooth wear
Re = xlsread(filename,5,'T2:T44');%Reynolds number function
ROP1 = xlsread(filename,5,'P2:P44'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a


a1 = 394.904007752955e+000;
a2 = -37.7677033360600e-003;
a3 = 325.542696406884e-003;
a4 = 2.61927704613186e-003;
a5 = -22.5482606974543e-003;
```

```
a6 =  750.649155500430e-003;
a7 = 0.00000000000000e+000;
a8 = -118.658764197424e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 398-409m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,6,'O2:O31');% h is the depth
gp = xlsread(filename,6,'V2:V31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,6,'U2:U31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,6,'Q2:Q31'); % wb is the Bit Weight function in lb/In.
wt = 0.002; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,6,'R2:R31'); %Revolutions per minute
Tw = xlsread(filename,6,'S2:S31'); %Tooth wear
Re = xlsread(filename,6,'T2:T31');%Reynolds number function
ROP1 = xlsread(filename,6,'P2:P31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 50.8234340996313e+003;
a2 = -4.14639290989268e+000;
a3 = 159.474923314459e+000;
a4 = -17.1489526189478e+000;
a5 = 268.168420560892e-003;
a6 =  -3.96818345495474e+000;
a7 = 0.00000000000000e+000;
a8 = -491.177247442036e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 409-428m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,7,'O2:O34');% h is the depth
gp = xlsread(filename,7,'V2:V34');%gp is the pore gradient of the formation
Ecd = xlsread(filename,7,'U2:U34'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,7,'Q2:Q34'); % wb is the Bit Weight function in lb/In.
wt = 0.002; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,7,'R2:R34'); %Revolutions per minute
Tw = xlsread(filename,7,'S2:S34'); %Tooth wear
Re = xlsread(filename,7,'T2:T34');%Reynolds number function
ROP1 = xlsread(filename,7,'P2:P34'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
```

```
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;


a1 = -5.56739846163144e+003;
a2 = 443.845443843781e-003;
a3 = -16.9271650173581e+000;
a4 = 1.66541787038885e+000;
a5 = 339.629514073584e-003;
a6 =  -3.61525844614138e+000;
a7 = 0.00000000000000e+000;
a8 = 144.189780901177e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 428-472m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,8,'O2:O34');% h is the depth
gp = xlsread(filename,8,'V2:V34');%gp is the pore gradient of the formation
Ecd = xlsread(filename,8,'U2:U34'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,8,'Q2:Q34'); % wb is the Bit Weight function in lb/In.
wt = 0.21; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,8,'R2:R34'); %Revolutions per minute
Tw = xlsread(filename,8,'S2:S34'); %Tooth wear
Re = xlsread(filename,8,'T2:T34');%Reynolds number function
ROP1 = xlsread(filename,8,'P2:P34'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 5.59159120351966e+003;
a2 = -459.278471713719e-003;
a3 =  16.5133522943078e+000;
a4 = -1.68799859112381e+000;
a5 = 29.9177201116451e-003;
a6 = 3.00329100052185e+000;
a7 = 0.00000000000000e+000;
a8 = 582.846349384066e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a' values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 472-684m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,9,'P2:P48');% h is the depth
gp = xlsread(filename,9,'W2:W48');%gp is the pore gradient of the formation
Ecd = xlsread(filename,9,'V2:V48'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,9,'R2:R48'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
```

```
N = xlsread(filename,9,'S2:S48'); %Revolutions per minute
Tw = xlsread(filename,9,'T2:T48'); %Tooth wear
Re = xlsread(filename,9,'U2:U48');%Reynolds number function
ROP1 = xlsread(filename,9,'Q2:Q48'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 56.1660129782400e+000;
a2 = -7.04062378370111e-003;
a3 = -10.6330093256751e-003;
a4 = 259.172394065107e-006;
a5 = 169.870261025757e-003;
a6 = -6.76339362197307e+000;
a7 = 0.00000000000000e+000;
a8 = 73.2655853935928e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 684-772.97m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,10,'P2:P36');% h is the depth
gp = xlsread(filename,10,'W2:W36');%gp is the pore gradient of the formation
Ecd = xlsread(filename,10,'V2:V36'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,10,'R2:R36'); % wb is the Bit Weight function in lb/In.
wt = 0.21; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,10,'S2:S36'); %Revolutions per minute
Tw = xlsread(filename,10,'T2:T36'); %Tooth wear
Re = xlsread(filename,10,'U2:U36');%Reynolds number function
ROP1 = xlsread(filename,10,'Q2:Q36'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 1.96257728281597e+000;
a2 =  1.69287993733874e-003;
a3 =  1.97335211372301e-003;
a4 = -1.66696458369254e-003;
a5 = -444.729736036671e-003;
a6 =  -9.18838642286026e+000;
a7 = 0.00000000000000e+000;
```

```
a8 = -1.56755815672909e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1010-1098m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,12,'P2:P58');% h is the depth
gp = xlsread(filename,12,'W2:W58');%gp is the pore gradient of the formation
Ecd = xlsread(filename,12,'V2:V58'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,12,'R2:R58'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,12,'S2:S58'); %Revolutions per minute
Tw = xlsread(filename,12,'T2:T58'); %Tooth wear
Re = xlsread(filename,12,'U2:U58');%Reynolds number function
ROP1 = xlsread(filename,12,'Q2:Q58'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = -43.2378272975224e+000;
a2 = 7.95451723797085e-003;
a3 = 15.2629132600629e-003;
a4 = -1.26161474248324e-003;
a5 = -147.007964483090e-003;
a6 = -1.48323337074801e+000;
a7 = 0.00000000000000e+000;
a8 =  -2.03031253542035e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1098-1135.95m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,13,'P2:P32');% h is the depth
gp = xlsread(filename,13,'W2:W32');%gp is the pore gradient of the formation
Ecd = xlsread(filename,13,'V2:V32'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,13,'R2:R32'); % wb is the Bit Weight function in lb/In.
wt = 0.21; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,13,'S2:S32'); %Revolutions per minute
Tw = xlsread(filename,13,'T2:T32'); %Tooth wear
Re = xlsread(filename,13,'U2:U32');%Reynolds number function
ROP1 = xlsread(filename,13,'Q2:Q32'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
```

```
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a
a1 = 291.455178946643e+000;
a2 = -40.0363558631094e-003;
a3 = -55.1868407820144e-003;
a4 = 1.21269073273318e-003;
a5 = -467.411912774862e-003;
a6 = -1.67306447653336e+000;
a7 = 0.00000000000000e+000;
a8 = 1.28241484697596e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1135.95-1375.37m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,14,'P2:P31');% h is the depth
gp = xlsread(filename,14,'W2:W31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,14,'V2:V31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,14,'R2:R31'); % wb is the Bit Weight function in lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,14,'S2:S31'); %Revolutions per minute
Tw = xlsread(filename,14,'T2:T31'); %Tooth wear
Re = xlsread(filename,14,'U2:U31');%Reynolds number function
ROP1 = xlsread(filename,14,'Q2:Q31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 161.669772574445e+000;
a2 = -24.5611534543853e-003;
a3 = -56.2559438500779e-003;
a4 = 2.41452909557479e-003;
a5 = -397.000146362921e-003;
a6 = -529.503210605178e-003;
a7 = 0.00000000000000e+000;
a8 = 4.42472908805053e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1375.37-1410.7m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,15,'P2:P31');% h is the depth
gp = xlsread(filename,15,'W2:W31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,15,'V2:V31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,15,'R2:R31'); % wb is the Bit Weight function in lb/In.
wt = 0.002; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,15,'S2:S31'); %Revolutions per minute
Tw = xlsread(filename,15,'T2:T31'); %Tooth wear
Re = xlsread(filename,15,'U2:U31');%Reynolds number function
```

```
ROP1 = xlsread(filename,15,'Q2:Q31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 109.200036132470e+000;
a2 = -9.53772936506014e-003;
a3 = -8.36067223363128e-003;
a4 = -2.38176298898641e-003;
a5 = 182.034752224796e-003;
a6 = 1.76201761877954e+000;
a7 = 0.00000000000000e+000;
a8 = -3.93838555811653e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1410.7-1970m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,16,'P2:P41');% h is the depth
gp = xlsread(filename,16,'W2:W41');%gp is the pore gradient of the formation
Ecd = xlsread(filename,16,'V2:V41'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,16,'R2:R41'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,16,'S2:S41'); %Revolutions per minute
Tw = xlsread(filename,16,'T2:T41'); %Tooth wear
Re = xlsread(filename,16,'U2:U41');%Reynolds number function
ROP1 = xlsread(filename,16,'Q2:Q41'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a
a1 = 28.6668965850636e+000;
a2 = -2.72307310762912e-003;
a3 = -7.08899492392483e-003;
a4 = 62.4889591415790e-006;
a5 = -240.694733477151e-003;
a6 = 3.50669604156615e+000;
a7 = 0.00000000000000e+000;
a8 = -63.1321024496928e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1970-1996.69m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,17,'P2:P31');% h is the depth
gp = xlsread(filename,17,'W2:W31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,17,'V2:V31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,17,'R2:R31'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.21; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,17,'S2:S31'); %Revolutions per minute
Tw = xlsread(filename,17,'T2:T31'); %Tooth wear
Re = xlsread(filename,17,'U2:U31');%Reynolds number function
ROP1 = xlsread(filename,17,'Q2:Q31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a;
a1 = 504.451549326401e+000;
a2 =  -61.0485777980555e-003;
a3 = -149.504894040251e-003;
a4 = 603.146416219243e-006;
a5 = -171.137947920015e-003;
a6 = -2.55327701240369e+000;
a7 = 0.00000000000000e+000;
a8 = 1.50174076490773e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 1996.69-2057.52m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,18,'P2:P31');% h is the depth
gp = xlsread(filename,18,'W2:W31');%gp is the pore gradient of the formation
Ecd = xlsread(filename,18,'V2:V31'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,18,'R2:R31'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,18,'S2:S31'); %Revolutions per minute
Tw = xlsread(filename,18,'T2:T31'); %Tooth wear
Re = xlsread(filename,18,'U2:U31');%Reynolds number function
ROP1 = xlsread(filename,18,'Q2:Q31'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
```

```
a = X\(log(ROP1));
format longeng;
a
a1 = -335.560209809289e+000;
a2 = 27.9582678880694e-003;
a3 = 119.443257527729e-003;
a4 = -254.362143480168e-006;
a5 = 91.0711211573296e-003;
a6 = -262.456554018142e-003;
a7 = 0.00000000000000e+000;
a8 = -569.451169759486e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 2057.52-2060.71m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,19,'P2:P35');% h is the depth
gp = xlsread(filename,19,'W2:W35');%gp is the pore gradient of the formation
Ecd = xlsread(filename,19,'V2:V35'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,19,'R2:R35'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.002; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,19,'S2:S35'); %Revolutions per minute
Tw = xlsread(filename,19,'T2:T35'); %Tooth wear
Re = xlsread(filename,19,'U2:U35');%Reynolds number function
ROP1 = xlsread(filename,19,'Q2:Q35'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a
a1 = 280.345360915344e+000;
a2 = 43.8245142316570e-003;
a3 = -189.215931086155e-003;
a4 = -849.749296528437e-006;
a5 = -46.0526134848581e-003;
a6 = 3.49717673499803e+000;
a7 = 0.00000000000000e+000;
a8 = -1.51896944877940e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

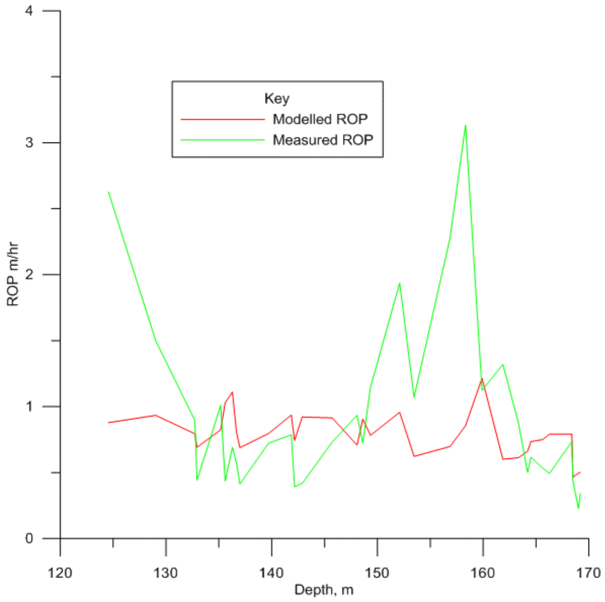
```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 2060.71-2082.95m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,20,'P2:P35');% h is the depth
gp = xlsread(filename,20,'W2:W35');%gp is the pore gradient of the formation
Ecd = xlsread(filename,20,'V2:V35'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,20,'R2:R35'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.21; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,20,'S2:S35'); %Revolutions per minute
Tw = xlsread(filename,20,'T2:T35'); %Tooth wear
Re = xlsread(filename,20,'U2:U35');%Reynolds number function
ROP1 = xlsread(filename,20,'Q2:Q35'); %ROP, in ft/hour
x2 = 10000-h;
```

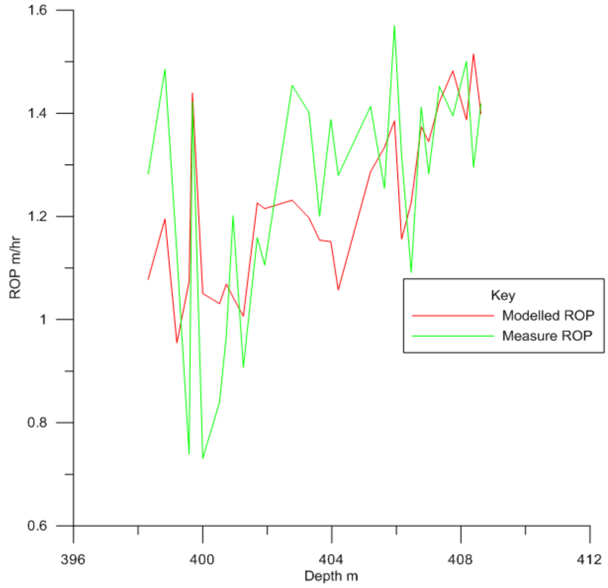
```
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x6 x7 x8];
a = X\(log(ROP1));
format longeng;
a
a1 = -371.204347733175e+000;
a2 = 37.0988959259594e-003;
a3 = 113.652896492816e-003;
a4 = -170.659517205050e-006;
a5 = 513.715659630697e-003;
a6 = -25.3200725493152e+000;
a7 = 0.00000000000000e+000;
a8 = -500.053083099466e-003;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP
```

```
%This code is for finding 'a'values for drilling parameters and calculating the modelled ROP
%and other parameters for well MW-17 from 2082.95-2218m
filename = 'MW-17 From SI to US Field units.xls';
h = xlsread(filename,21,'P2:P40');% h is the depth
gp = xlsread(filename,21,'W2:W40');%gp is the pore gradient of the formation
Ecd = xlsread(filename,21,'V2:V40'); %Ecd is the equivalent circulation density of drilling
fluid
wb = xlsread(filename,21,'R2:R40'); % wb is the Bit Weight function in 1000 lb/In.
wt = 0.6; %wt is the threshold weight on bit in 1000 lb/In.
c = 1;%is the constant for changing the percentages to check sensitivity
N = xlsread(filename,21,'S2:S40'); %Revolutions per minute
Tw = xlsread(filename,21,'T2:T40'); %Tooth wear
Re = xlsread(filename,21,'U2:U40');%Reynolds number function
ROP1 = xlsread(filename,21,'Q2:Q40'); %ROP, in ft/hour
x2 = 10000-h;
x3 = (h.^0.69).*(gp-9);
x4 = h.*(gp-Ecd);
x5 = log((c.*wb-wt)/(4-wt));
lengthx5 = length(x5);
for k = 1:lengthx5
    if isreal(x5(k))
       x5(k) = x5(k);
    else
        x5(k) = 0;
    end
end
x5;
x6 = log(N/100);
x7 = -Tw;
x8 = Re;
X = [ones(size(x2)) x2 x3 x4 x5 x7 x6 x8];
a = X\(log(ROP1));
format longeng;
a
a1 = -77.3582938226979e+000;
a2 =  7.26357012980299e-003;
a3 = 19.6037455253022e-003;
a4 = 393.900955298549e-006;
a5 = -647.898477012809e-003;
a6 = -3.97192899119828e+000;
a7 = 0.00000000000000e+000;
a8 = 1.09301094278280e+000;
ROP = exp(a1+a2.*x2+a3.*x3+a4.*x4+a5.*x5+a6.*x6+a7.*x7+a8.*x8);
ROP;
```

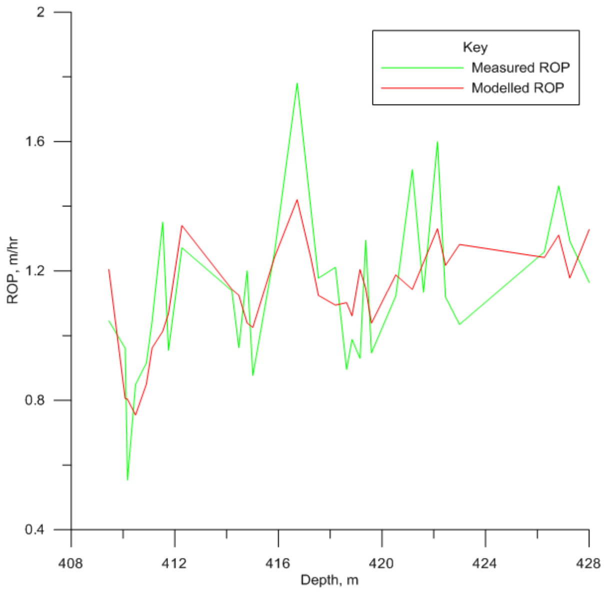
APPENDIX II: Modelling ROP

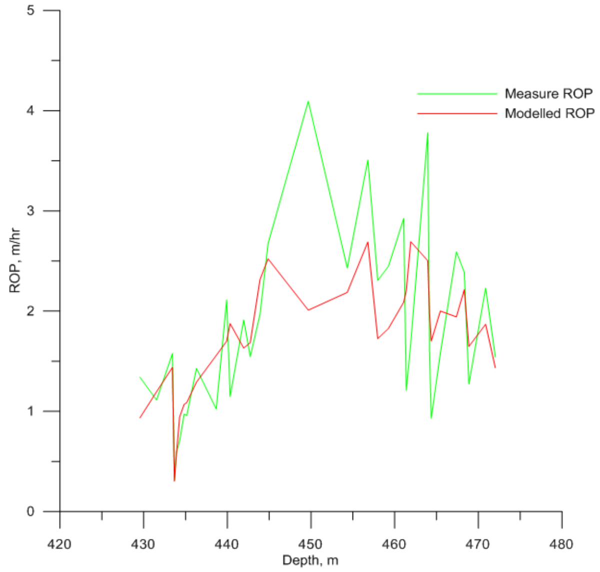
Result of modelling for Rate of Penetration for intermediate hole:

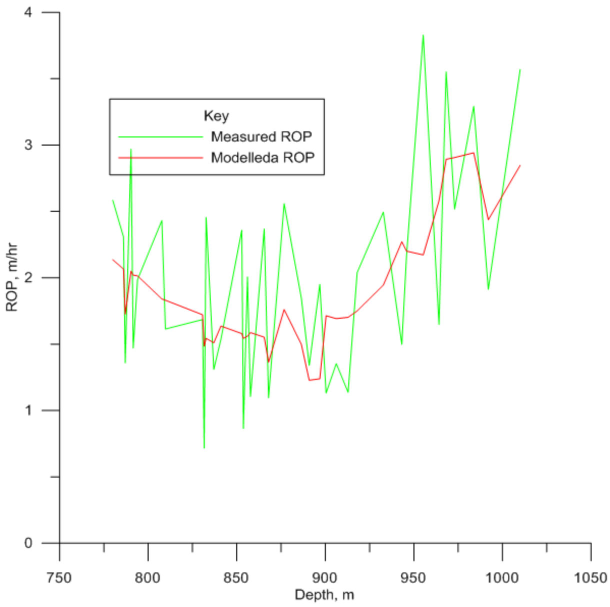




Result of modelling for Rate of Penetration for the production hole:



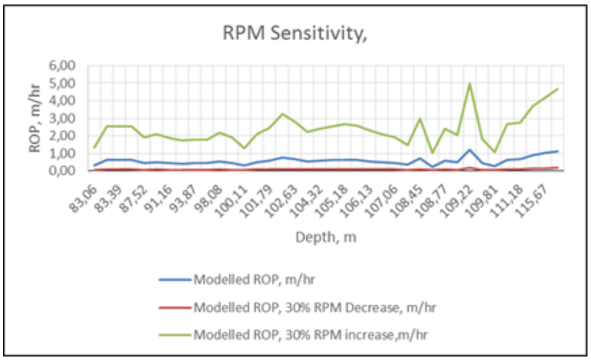


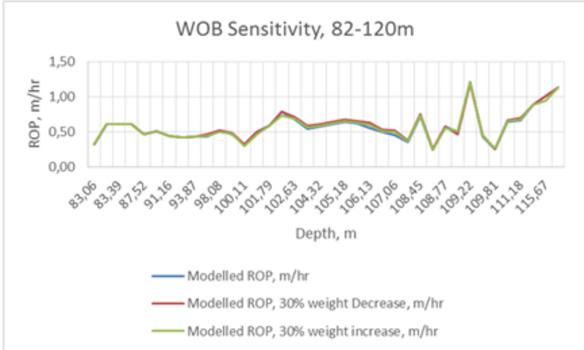


Key
Measured ROP
Modelleda ROP
ROP, m/hr
Depth, m
0
1
2
3
4
750
800
850
900
950
1000
1050

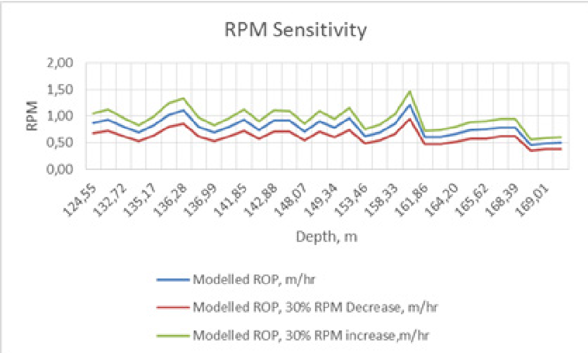
APPENDIX III: Sensitivity analysis

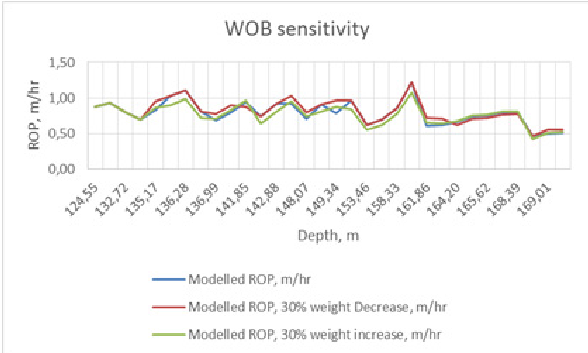
Sensitivity analysis for the surface hole:

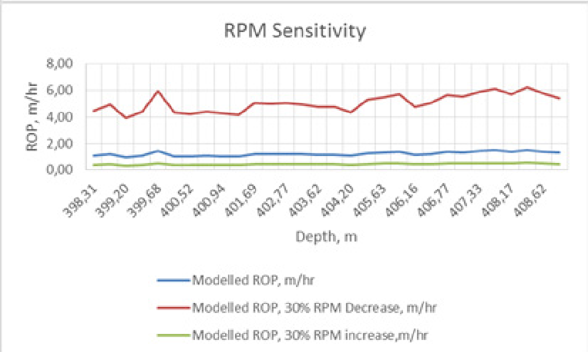


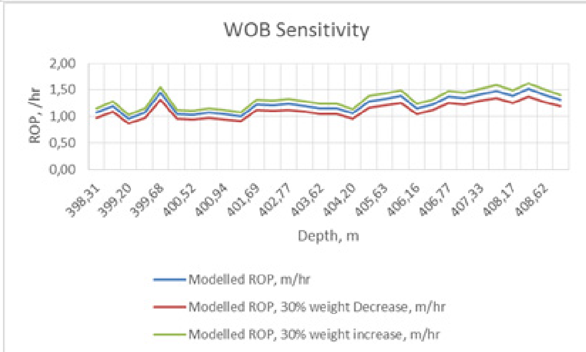


Sensitivity analysis for the intermediate hole:

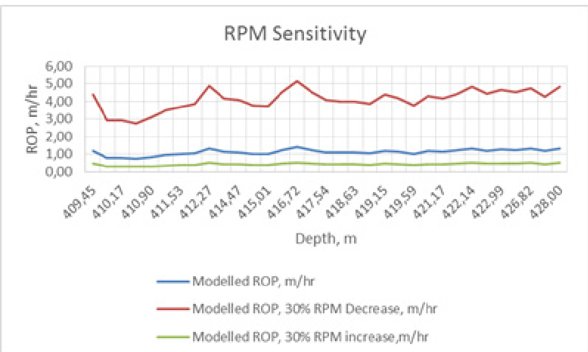


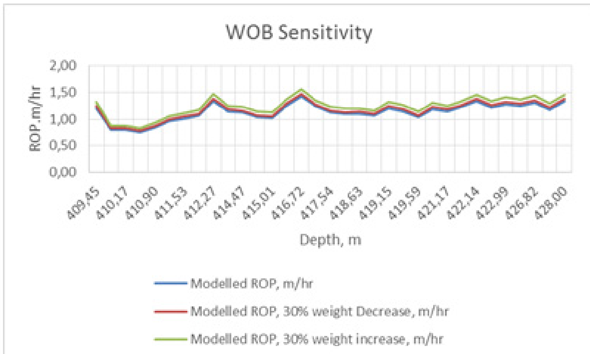


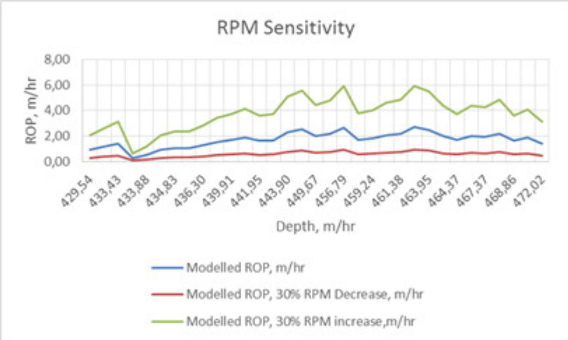


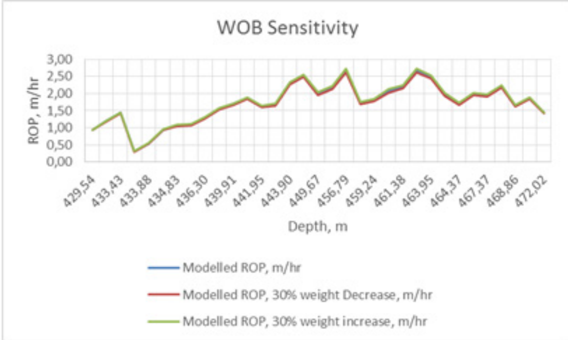


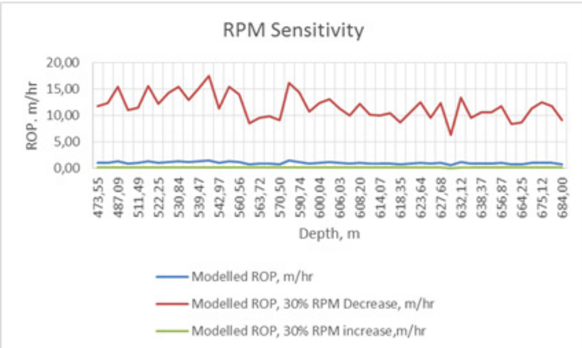
Sensitivity analysis for the production hole:

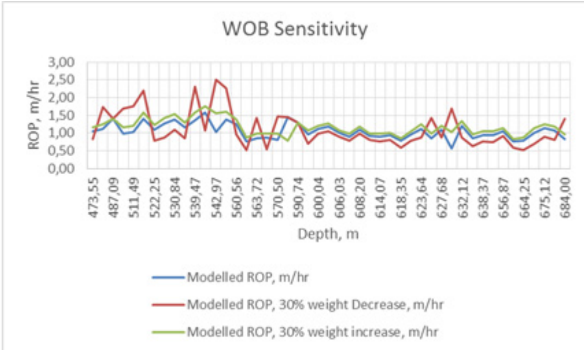


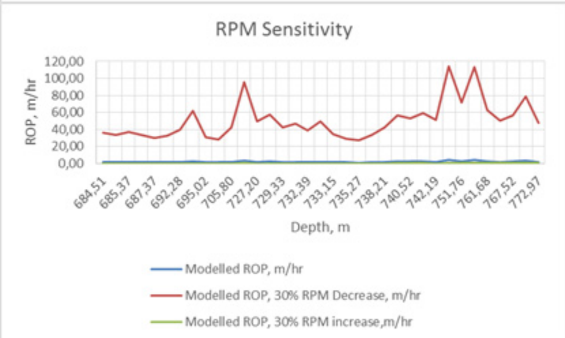


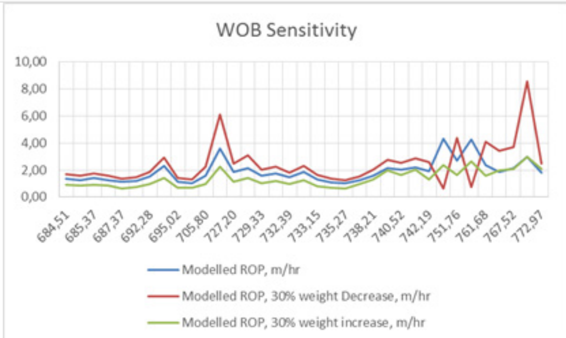




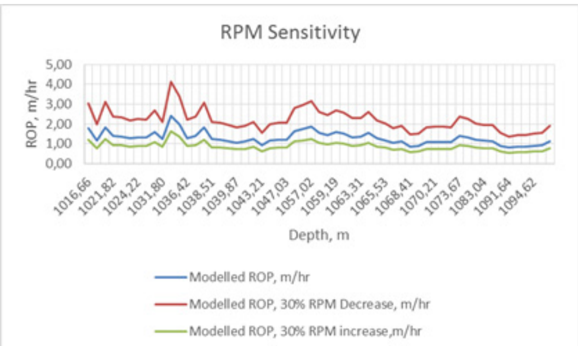


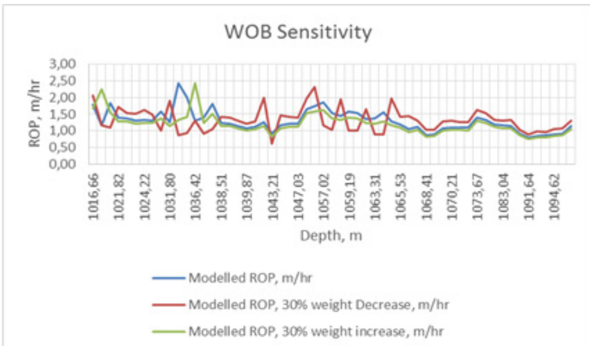


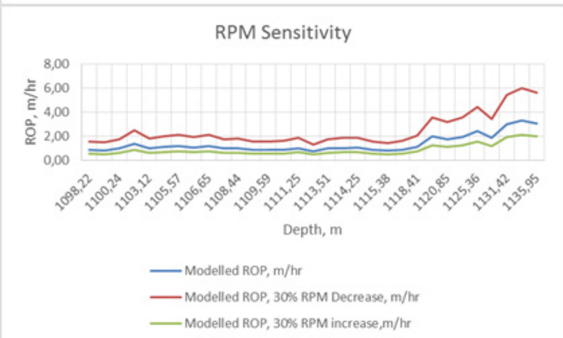


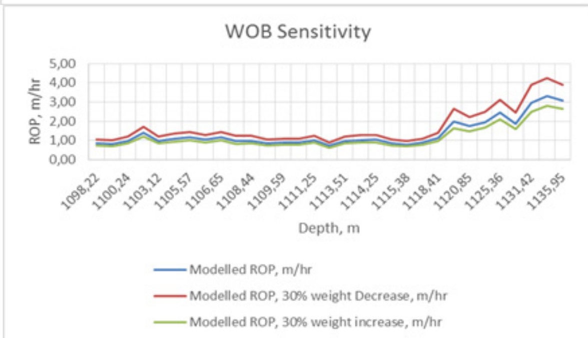


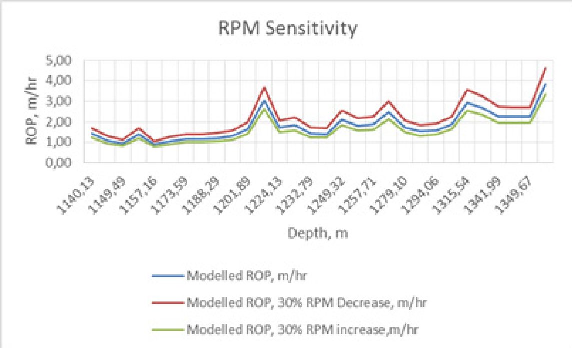
Sensitivity analysis for the open hole:

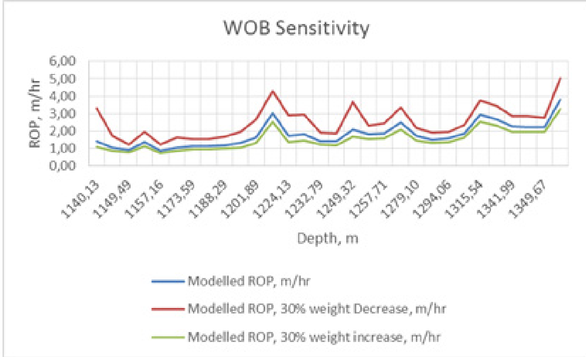


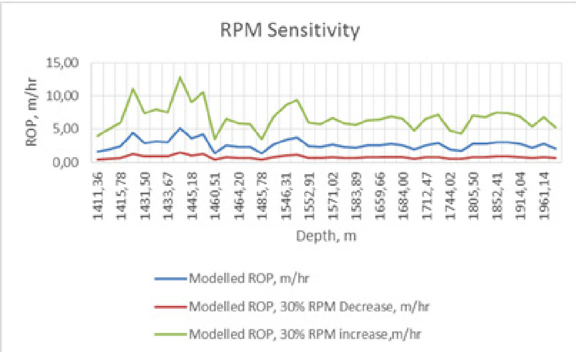


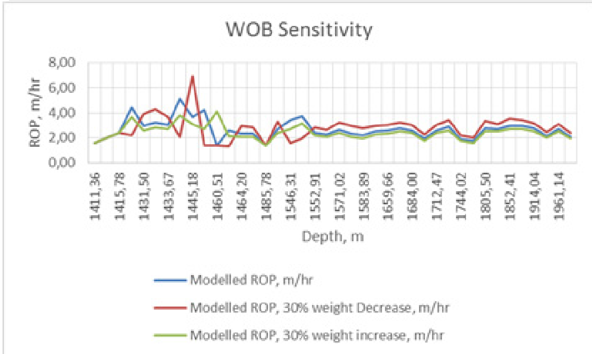


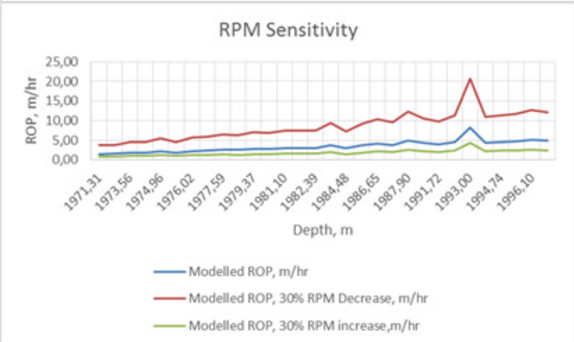


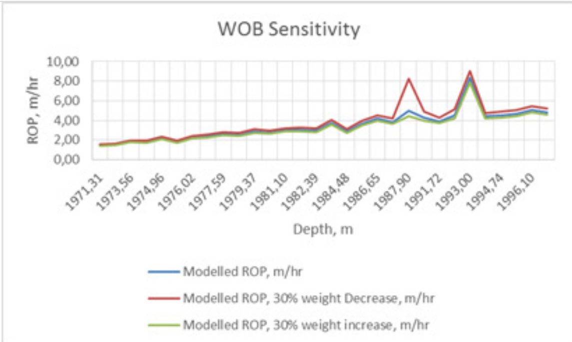

RPM Sensitivity
ROP, m/hr
5,00 4,00 3,00 2,00 1,00 0,00
1140,13 1149,49 1157,16 1173,59 1188,29 1201,89 1224,13 1232,79 1249,32 1257,71 1279,10 1294,06 1315,54 1341,99 1349,67
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr

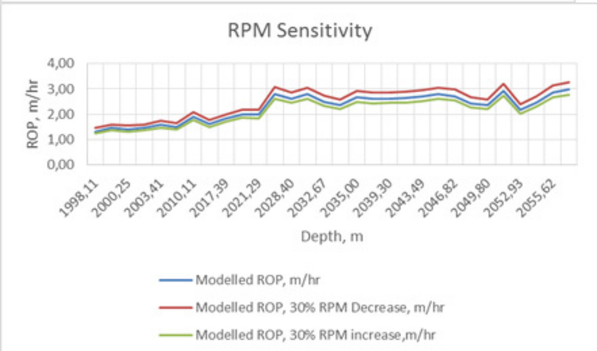

WOB Sensitivity
ROP, m/hr
6,00 5,00 4,00 3,00 2,00 1,00 0,00
1140,13 1149,49 1157,16 1173,59 1188,29 1201,89 1224,13 1232,79 1249,32 1257,71 1279,10 1294,06 1315,54 1341,99 1349,67
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

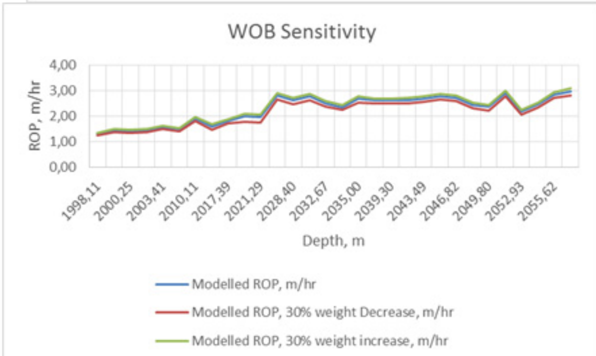

RPM Sensitivity
ROP, m/hr
15,00 10,00 5,00 0,00
1411,36 1415,78 1431,50 1433,67 1445,18 1460,51 1464,20 1485,78 1546,31 1552,91 1571,02 1583,89 1659,66 1684,00 1712,47 1744,02 1805,50 1852,41 1914,04 1961,14
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr

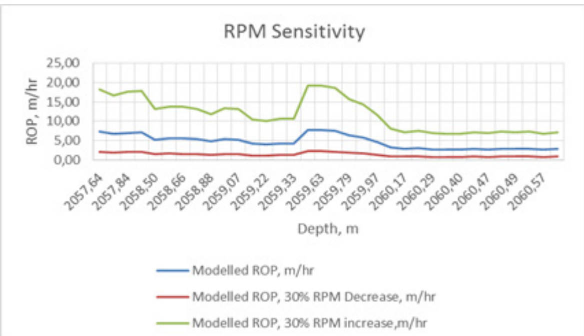

WOB Sensitivity
ROP, m/hr
8,00 6,00 4,00 2,00 0,00
1411,36 1415,78 1431,50 1433,67 1445,18 1460,51 1464,20 1485,78 1546,31 1552,91 1571,02 1583,89 1659,66 1684,00 1712,47 1744,02 1805,50 1852,41 1914,04 1961,14
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

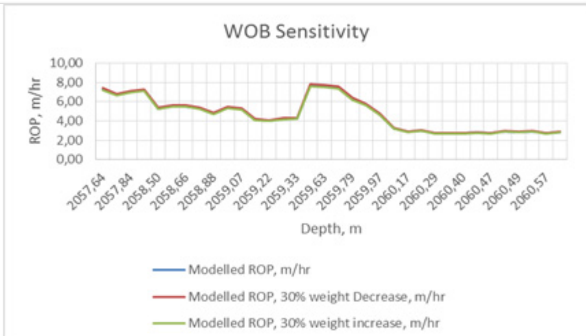

RPM Sensitivity
ROP, m/hr
25,00 20,00 15,00 10,00 5,00 0,00
1971,31 1973,56 1974,96 1976,02 1977,59 1979,37 1981,10 1982,39 1984,48 1986,65 1987,90 1991,72 1993,00 1994,74 1996,10
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr

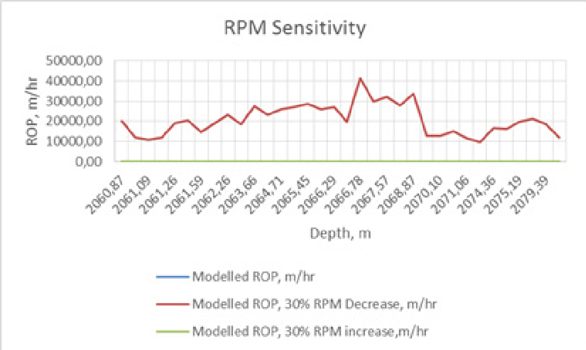

WOB Sensitivity
ROP, m/hr
10,00 8,00 6,00 4,00 2,00 0,00
1971,31 1973,56 1974,96 1976,02 1977,59 1979,37 1981,10 1982,39 1984,48 1986,65 1987,90 1991,72 1993,00 1994,74 1996,10
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

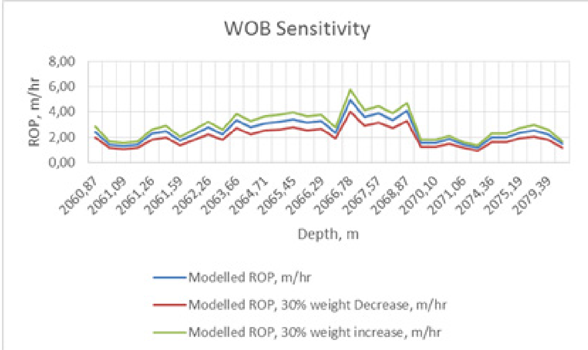

RPM Sensitivity
ROP, m/hr
4,00 3,00 2,00 1,00 0,00
1998,11 2000,25 2003,41 2010,11 2017,39 2021,29 2028,40 2032,67 2035,00 2039,30 2043,49 2046,82 2049,80 2052,93 2055,62
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr

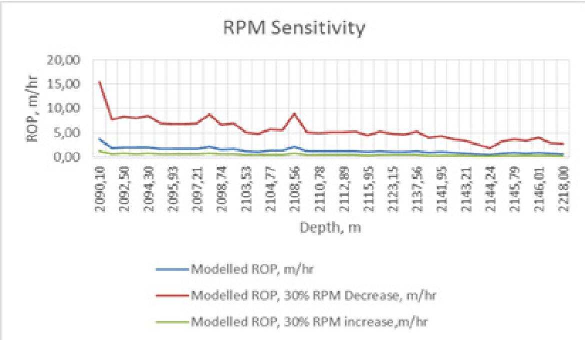

WOB Sensitivity
ROP, m/hr
4,00 3,00 2,00 1,00 0,00
1998,11 2000,25 2003,41 2010,11 2017,39 2021,29 2028,40 2032,67 2035,00 2039,30 2043,49 2046,82 2049,80 2052,93 2055,62
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

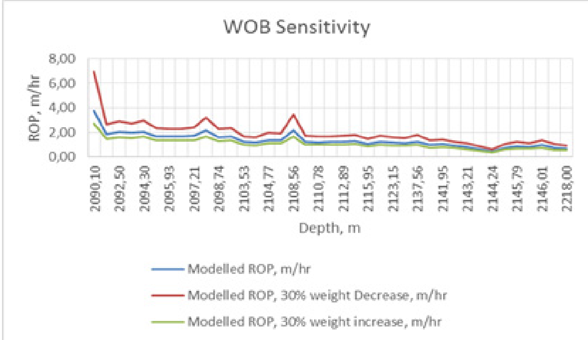

RPM Sensitivity
ROP, m/hr
25,00 20,00 15,00 10,00 5,00 0,00
2057,64 2057,84 2058,50 2058,66 2058,88 2059,07 2059,22 2059,33 2059,63 2059,79 2059,97 2060,17 2060,29 2060,40 2060,47 2060,49 2060,57
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr


WOB Sensitivity
ROP, m/hr
10,00 8,00 6,00 4,00 2,00 0,00
2057,64 2057,84 2058,50 2058,66 2058,88 2059,07 2059,22 2059,33 2059,63 2059,79 2059,97 2060,17 2060,29 2060,40 2060,47 2060,49 2060,57
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr


RPM Sensitivity
ROP, m/hr
50000,00
40000,00
30000,00
20000,00
10000,00
0,00
2060,87
2061,09
2061,26
2061,59
2062,26
2063,66
2064,71
2065,45
2066,29
2066,78
2067,57
2068,87
2070,10
2071,06
2074,36
2075,19
2079,39
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr

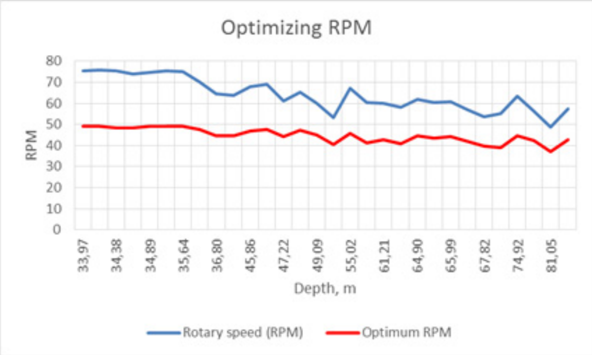

WOB Sensitivity
ROP, m/hr
8,00
6,00
4,00
2,00
0,00
2060,87
2061,09
2061,26
2061,59
2062,26
2063,66
2064,71
2065,45
2066,29
2066,78
2067,57
2068,87
2070,10
2071,06
2074,36
2075,19
2079,39
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

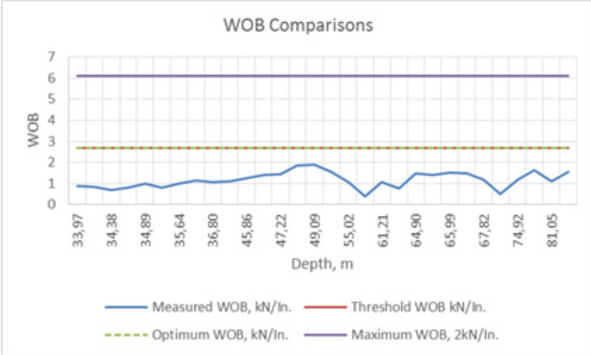

RPM Sensitivity
ROP, m/hr
20,00
15,00
10,00
5,00
0,00
2090,10
2092,50
2094,30
2095,93
2097,21
2098,74
2103,53
2104,77
2108,56
2110,78
2112,89
2115,95
2123,15
2137,56
2141,95
2143,21
2144,24
2145,79
2146,01
2218,00
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% RPM Decrease, m/hr
Modelled ROP, 30% RPM increase,m/hr


WOB Sensitivity
ROP, m/hr
8,00
6,00
4,00
2,00
0,00
2090,10
2092,50
2094,30
2095,93
2097,21
2098,74
2103,53
2104,77
2108,56
2110,78
2112,89
2115,95
2123,15
2137,56
2141,95
2143,21
2144,24
2145,79
2146,01
2218,00
Depth, m
Modelled ROP, m/hr
Modelled ROP, 30% weight Decrease, m/hr
Modelled ROP, 30% weight increase, m/hr

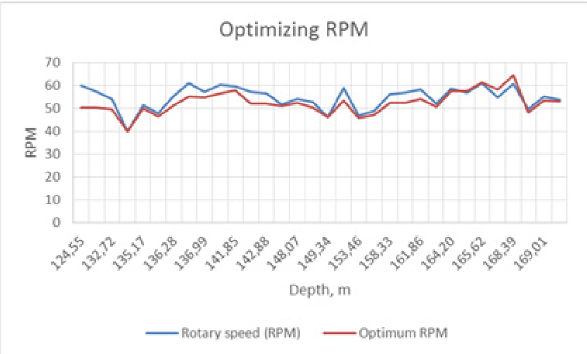
APPENDIX IV: Optimization results

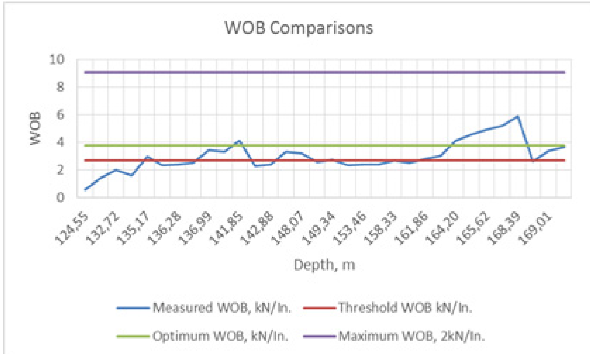
Optimization results for the surface hole

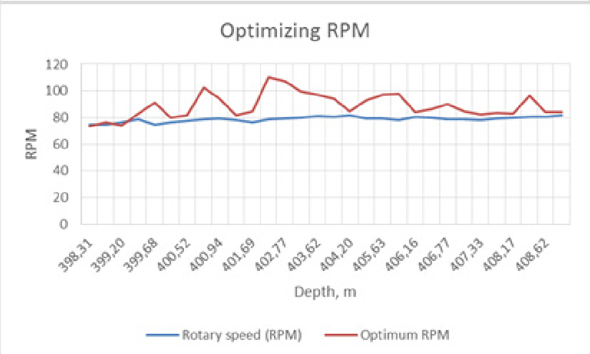


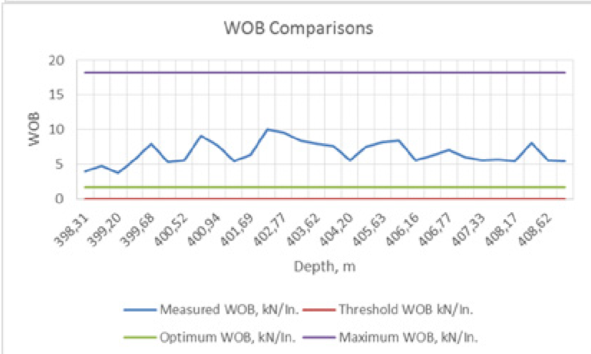


Optimization results for the intermediate hole

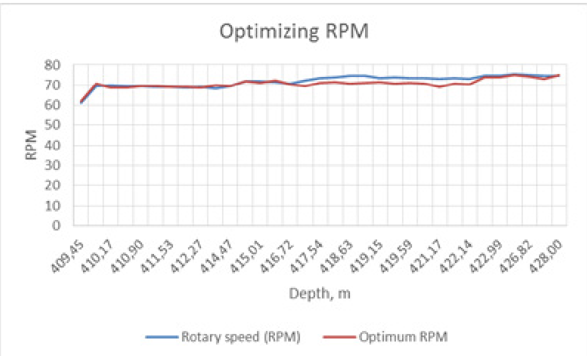


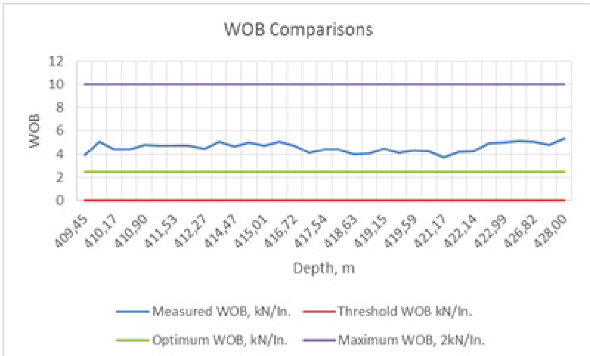


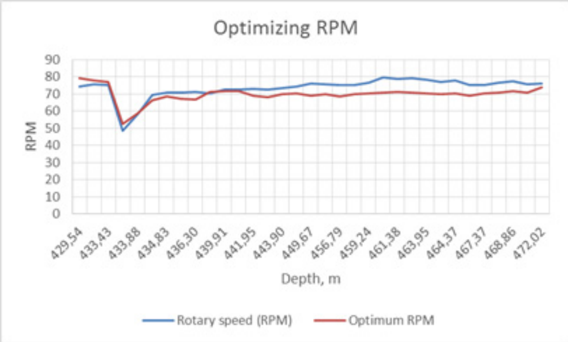


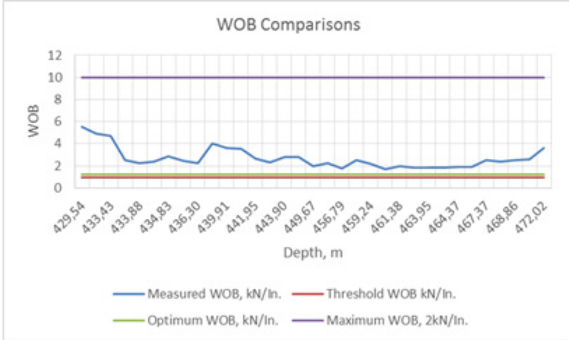


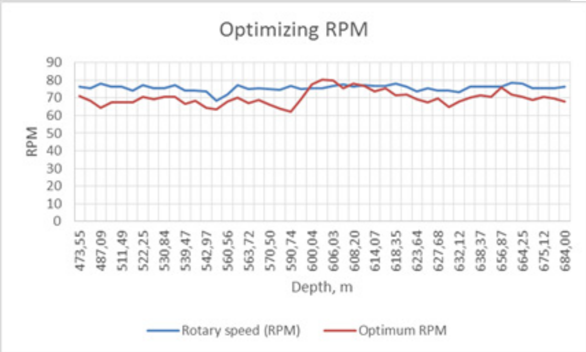
Optimization results for the production hole

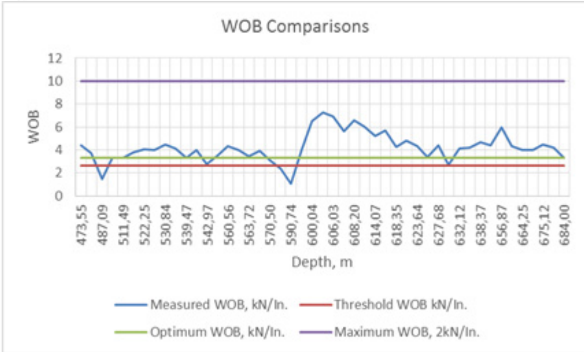




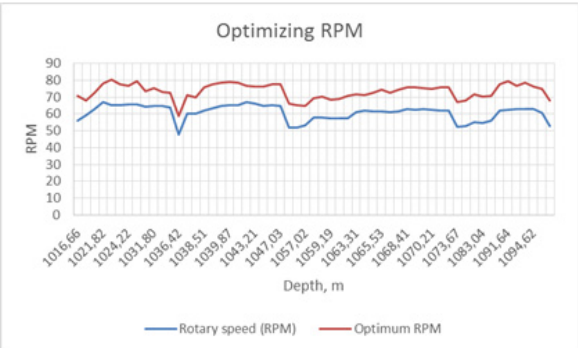


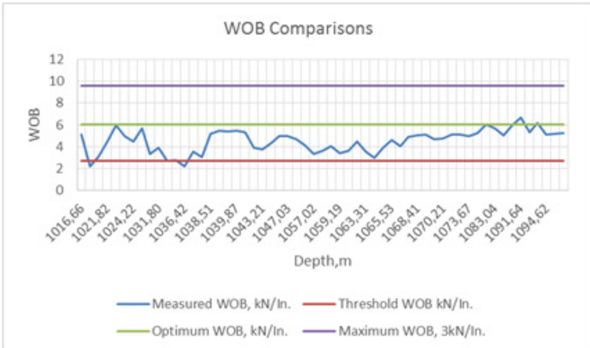


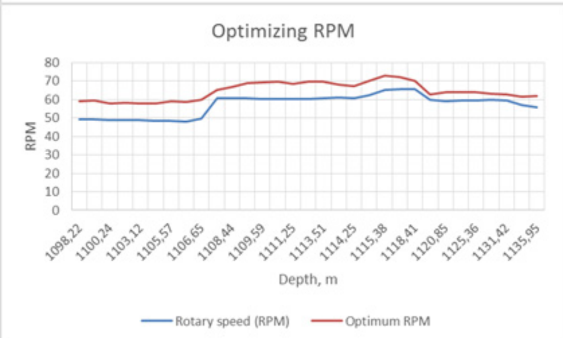


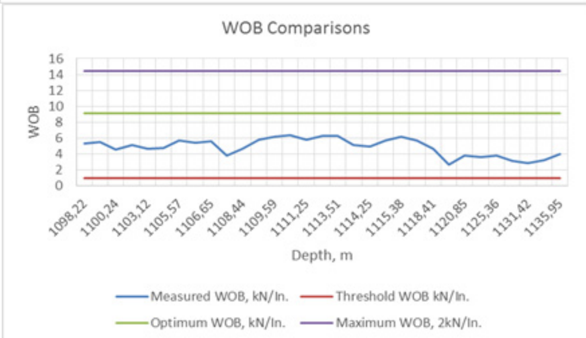


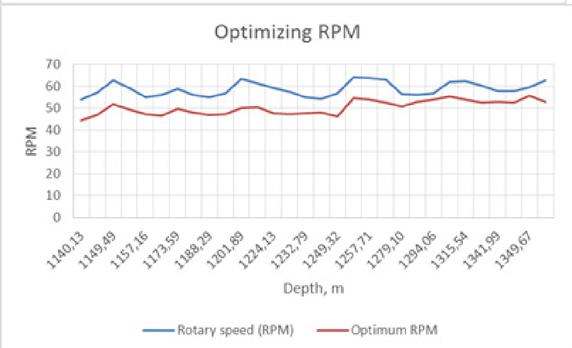
Optimization results for the open hole

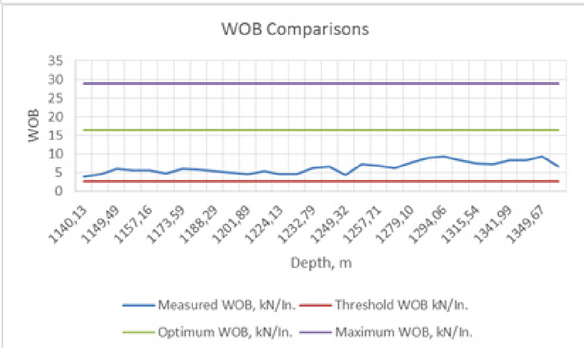


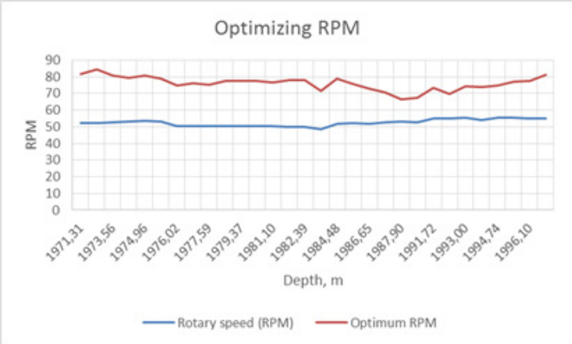


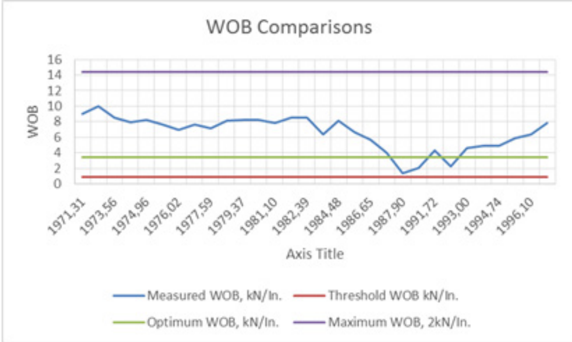


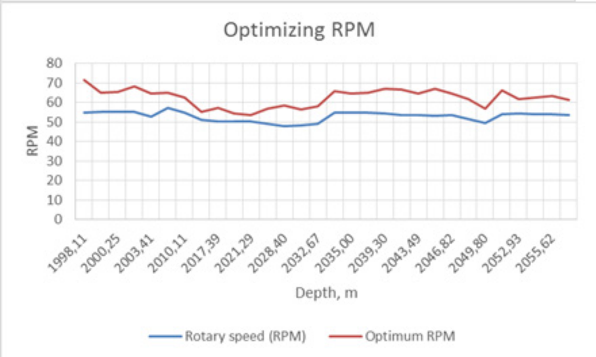


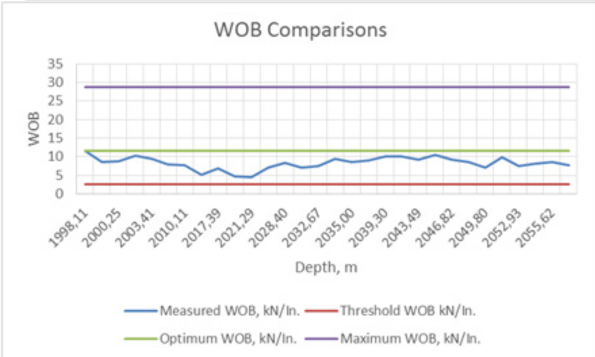


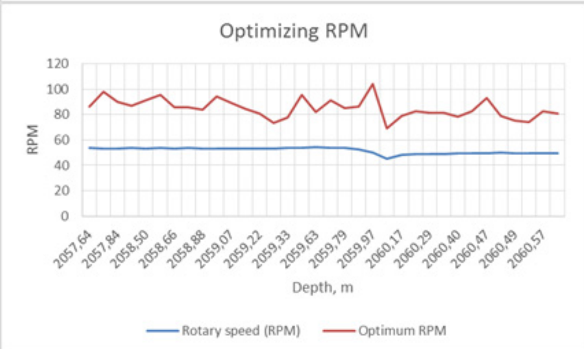


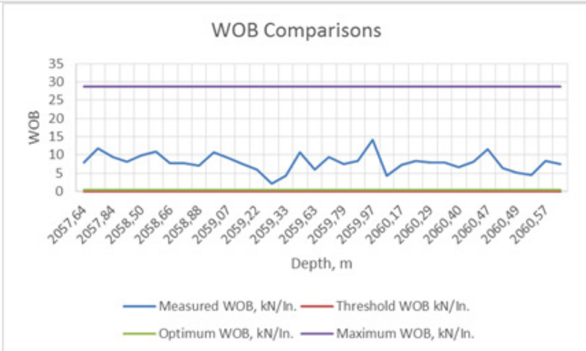

Optimizing RPM
RPM
Depth, m
Rotary speed (RPM)
Optimum RPM

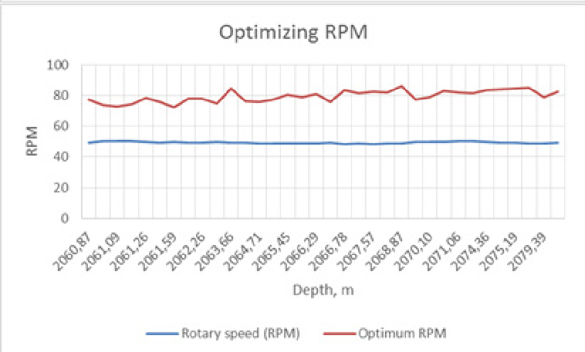

WOB Comparisons
WOB
Axis Title
Measured WOB, kN/In.
Threshold WOB kN/In.
Optimum WOB, kN/In.
Maximum WOB, 2kN/In.

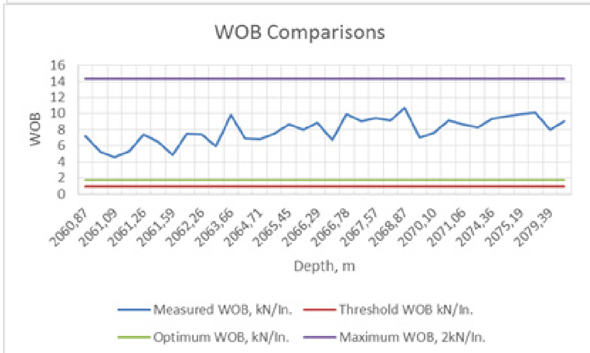

Optimizing RPM
RPM
Depth, m
Rotary speed (RPM)
Optimum RPM


WOB Comparisons
WOB
Depth, m
Measured WOB, kN/In.
Threshold WOB kN/In.
Optimum WOB, kN/In.
Maximum WOB, kN/In.


Optimizing RPM
RPM
Depth, m
Rotary speed (RPM)
Optimum RPM


WOB Comparisons
WOB
Depth, m
Measured WOB, kN/In.
Threshold WOB kN/In.
Optimum WOB, kN/In.
Maximum WOB, kN/In.


Optimizing RPM
RPM
Depth, m
Rotary speed (RPM)
Optimum RPM


WOB Comparisons
WOB
Depth, m
Measured WOB, kN/In.
Threshold WOB kN/In.
Optimum WOB, kN/In.
Maximum WOB, 2kN/In.