Modelling of Geothermal Drilling Parameters —
A Case Study of Well MW-17 in Menengai Kenya

Thomas Miyora, Magnús Pór Jónsson, and Sverrir Pórhallsson

miyorato@yahoo.com • magnusj@hi.is • Sverrir.Thorhallsson@isor.is

Keywords
Modelling, drilling parameters, model theory, measured and modeled parameters, multiple linear regression

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. 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.

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 15,000MWe (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
Miyora, et al.

MW-1. By November 2014 Over 30 geothermal wells had been drilled in Menengai field. Drilling is ongoing with 6 large rigs and 1 more is being commissioned at the field and is expected to start drilling by May 2015.

The objective of this paper 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. 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 are 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’s’) from Matlab. Matlab was used in executing the multiple linear regression to calculate the regressor constants.

The modelling approach applied in this paper 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 weight 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 modeling 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 show alternating layers of different types of rocks from the surface to the bottom of the well (Figure 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.

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 rotation speeds 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 paper is to attempt to do a model of the drilling process and get the output as the rate of penetration. Thereafter the model can be used to carry out optimization of the rate of penetration and also do a sensitivity analysis of the various parameters that contribute to change of rate of penetration.

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 bottomhole, 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.

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. 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.

The manpower requirement at the rig is summarized in figure 1.

![Figure 1. Personnel involved in drilling (Adapted from Ford, 2004).](image)

3. Methodology of the Model

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 Mathematical Model for Rate of Penetration

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:

\[
\frac{dh}{dt} = e^{(a_1 + \sum_{j=2}^{6} a_j x_j)}
\]

where,

\[
dh/dt = \text{rate of penetration} \\
h = \text{Depth, ft.} \\
t = \text{Time, hrs} \\
a_i = \text{Constants} \\
x_j = \text{Drilling parameters}
\]

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

\[
x_2 = 10000 - h
\]

\[
x_3 = h^{0.69}(g_p - 9)
\]

where,

\[
g_p = \text{Pore pressure gradient of the formation}
\]
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 $x_4$ 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

$$x_4 = h(g_p - p_e)$$  

where,

$p_e$ = 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

$$x_5 = \ln \left( \frac{\frac{w}{d} - \left( \frac{w}{d} \right)_t}{\frac{w}{d} - \left( \frac{w}{d} \right)_t} \right)^\frac{1}{2}$$

where,

$w/d$ = weight on bit (WOB) per inch of bit diameter, 1000lb/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

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

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 $a_7$ 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.

$$x_7 = -t_w$$

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 \( \left( \frac{N}{w/d} \right)^{0.5} \). 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:

\[ x_8 = \frac{\rho q}{350 \mu d_n} \]  

(8a)

where,

$\rho$ = Density, lb/gal

$q$ = Discharge, gal

$\mu$ = Apparent viscosity at 10000 sec$^{-1}$, cp

$d_n$ = Nozzle diameter, inches

This value can be estimated by equation 8b

\[ \mu = \mu_p + \frac{\tau_y}{20} \]  

(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 $a_i$ 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.

4. Data Analysis

From the methodology section, several variables are 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 1 below:

<table>
<thead>
<tr>
<th>Variables Measured While Drilling</th>
<th>Variables to be Calculated</th>
<th>Variables That Need Special Field Test/Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Equivalent circulation density</td>
<td>Threshold weight on bit</td>
</tr>
<tr>
<td>Rate of penetration/ROP</td>
<td>Pore pressure gradient</td>
<td>Bit and nozzle diameter</td>
</tr>
<tr>
<td>Weight on Bit (WOB)</td>
<td></td>
<td>Fluid viscosity</td>
</tr>
<tr>
<td>Rotary speed (RPM)</td>
<td></td>
<td>Density of fluid</td>
</tr>
<tr>
<td>Flow rate</td>
<td></td>
<td>Tooth wear fraction</td>
</tr>
</tbody>
</table>

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 can be found in engineering books under the hydraulics and hydraulics models. Calculation of pore pressure gradient and equivalent circulation density will require use of bit and nozzle diameters, fluid viscosity and fluid density.

4.1 Variables Measured While Drilling

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; these 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 column. A typical raw data retrieved from a Drilling data acquisition and monitoring system for well MW-17 in Menengai is as shown in Table 2 on the following page.

4.2 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 below.

4.2.1 The Pore Pressure Gradient

Calculating $x_3$ 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,
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 14.

\[
P_p = P_l + \rho_f g (h_2 - h_1)
\]  

(14)

where

- \( P_p \) = Formation fluid pressure, Pa or psi at depth \( h_2 \),
- \( P_l \) = Formation fluid pressure, Pa or psi at depth \( h_1 \),
- \( \rho_f \) = 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 \( \rho_f g (h) \) where \( h \) is the depth at the point where the pressure is measured. Hence modifying equation 14 to get pore pressure gradient with units N/L or lb/gal becomes:

\[
P_{pg} = \frac{P_l + \rho_f g (h_2 - h_1)}{1000D}
\]

(15)

where

- \( P_{pg} \) = pore pressure gradient, N/L

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.

### Table 2. Part of the Raw Data for Well MW-17.

<table>
<thead>
<tr>
<th>Date and Time</th>
<th>Hole Depth m</th>
<th>Bit Depth m</th>
<th>ROP ( \text{m/min} )</th>
<th>WOB ( \text{kgf} )</th>
<th>KIP Torque ( \text{lb f} )</th>
<th>RPM</th>
<th>Pump Pressure ( \text{Psi} )</th>
<th>Pump Rate ( \text{bbl/hr} )</th>
<th>Pump Rate ( \text{bbl/hr} )</th>
<th>Surge Rate ( \text{bbl/hr} )</th>
<th>Flow In ( \text{lps} )</th>
<th>Linework</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013.08.25 09:18:04</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
<tr>
<td>2013.08.25 09:18:05</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
<tr>
<td>2013.08.25 09:17:04</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
<tr>
<td>2013.08.25 09:17:05</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
<tr>
<td>2013.08.25 09:17:06</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
<tr>
<td>2013.08.25 09:17:07</td>
<td>14.0</td>
<td>14.0</td>
<td>0</td>
<td>0</td>
<td>14.65</td>
<td>0</td>
<td>59.04</td>
<td>0</td>
<td>83.69</td>
<td>0</td>
<td>83.69</td>
<td>23.22</td>
</tr>
</tbody>
</table>

203
4.2.2 Equivalent Circulating Density (ECD)

Equivalent circulating density represents 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 16 below (Lyons et al., 2012).

\[
ECD = \frac{\text{Annulus friction pressure loss}}{1000h} + MW
\]  

Where

- \(\text{Annulus friction pressure loss}\) is in N/m²
- \(ECD\) = Equivalent circulating density, N/Litre
- \(h\) = Depth, m
- \(MW\) = Mud weight, N/Litre

The annulus friction pressure loss is calculated by applying appropriate engineering formula. The pore pressure gradient and ECD for well MW-17 have been plotted together as shown in figure 4.2.

4.3 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 weight on bit, the viscosity and yield strength of bentonite mud. This is discussed below how they were determined.

4.3.1 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 3. 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).

While drilling well MW-17, the data used to generate the graph in Figure 3 was not recorded at 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.

5. Case Study: Modelling Well MW-17 for ROP

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 4. 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.
6. 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.

6.1 The 'a' Coefficients

The modelling the ROP has been made by using the 'a\textsubscript{i}' values. Table 3 shows 'a\textsubscript{i}' values which are the result of the regression analysis for the various sections of the well. The 'a\textsubscript{i}' values were used to calculate the modelled ROP and the result is shown in the Figures 5-9.

The constant a\textsubscript{i} gives the formation strength and other factors that are not modelled such as effect of drilled cuttings etc. The a\textsubscript{i} constant varied considerably for the entire section of the well. The value of a\textsubscript{i} 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\textsubscript{2} represents the compaction effect on rate of penetration. Magnitude of a\textsubscript{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\textsubscript{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\textsubscript{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 (0-500m) in drilling and from -0.0017 to 0.0024 where aerated water was used (500 to 2218m).

![Figure 4. Subdivision of well MW-17 into 21 sections (MW-17 Completion report, 2013).](image)

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>a\textsubscript{1}</th>
<th>a\textsubscript{2}</th>
<th>a\textsubscript{3}</th>
<th>a\textsubscript{4}</th>
<th>a\textsubscript{5}</th>
<th>a\textsubscript{6}</th>
<th>a\textsubscript{7}</th>
<th>a\textsubscript{8}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-33.83</td>
<td>-1403.260</td>
<td>0.135</td>
<td>-4.406</td>
<td>1.089</td>
<td>0.000</td>
<td>-0.801</td>
<td>0</td>
<td>-0.079</td>
</tr>
<tr>
<td>33.83-82.57</td>
<td>-1539.95</td>
<td>0.16</td>
<td>1.29</td>
<td>-0.53</td>
<td>0.00</td>
<td>-2.10</td>
<td>0</td>
<td>0.04</td>
</tr>
<tr>
<td>82.57-120.95</td>
<td>-127.378</td>
<td>0.013</td>
<td>-0.089</td>
<td>-0.007</td>
<td>0.015</td>
<td>5.417</td>
<td>0</td>
<td>0.112</td>
</tr>
<tr>
<td>120.95-169.19</td>
<td>2039.05</td>
<td>-0.21</td>
<td>-1.79</td>
<td>0.40</td>
<td>0.04</td>
<td>0.70</td>
<td>0</td>
<td>-7.80</td>
</tr>
<tr>
<td>169.19-199.38</td>
<td>394.9040</td>
<td>-0.0378</td>
<td>0.3255</td>
<td>0.0026</td>
<td>-0.0225</td>
<td>0.7506</td>
<td>0</td>
<td>-0.1187</td>
</tr>
<tr>
<td>199.38-235.61</td>
<td>50823.43</td>
<td>4.15</td>
<td>159.47</td>
<td>-17.15</td>
<td>0.27</td>
<td>-3.97</td>
<td>0</td>
<td>-0.49</td>
</tr>
<tr>
<td>235.61-428</td>
<td>-5567.40</td>
<td>0.44</td>
<td>-16.93</td>
<td>1.67</td>
<td>0.34</td>
<td>-3.62</td>
<td>0</td>
<td>0.14</td>
</tr>
<tr>
<td>428-472</td>
<td>5591.59</td>
<td>-0.46</td>
<td>16.51</td>
<td>-1.69</td>
<td>0.03</td>
<td>3.00</td>
<td>0</td>
<td>0.58</td>
</tr>
<tr>
<td>472-684</td>
<td>56.1660</td>
<td>-0.0070</td>
<td>-0.0106</td>
<td>0.0003</td>
<td>0.1699</td>
<td>-6.7634</td>
<td>0</td>
<td>0.0733</td>
</tr>
<tr>
<td>684-772.97</td>
<td>1.9626</td>
<td>0.0017</td>
<td>0.0020</td>
<td>-0.0017</td>
<td>-0.4447</td>
<td>-9.1884</td>
<td>0</td>
<td>-1.5676</td>
</tr>
<tr>
<td>772.97-1010</td>
<td>-55.3423</td>
<td>0.00697</td>
<td>0.01438</td>
<td>0.00005</td>
<td>0.04089</td>
<td>0.24787</td>
<td>0</td>
<td>0.01742</td>
</tr>
<tr>
<td>1010-1098</td>
<td>-43.2378</td>
<td>0.0080</td>
<td>0.0153</td>
<td>-0.0013</td>
<td>-0.1470</td>
<td>-1.4832</td>
<td>0</td>
<td>-2.0303</td>
</tr>
<tr>
<td>1098-1135.95</td>
<td>291.4558</td>
<td>-0.04004</td>
<td>-0.05519</td>
<td>0.00121</td>
<td>-0.46741</td>
<td>-1.67306</td>
<td>0</td>
<td>1.28241</td>
</tr>
<tr>
<td>1135.95-1375.37</td>
<td>161.6698</td>
<td>-0.0246</td>
<td>-0.0563</td>
<td>0.0024</td>
<td>-0.3970</td>
<td>-0.5295</td>
<td>-4.4247</td>
<td></td>
</tr>
<tr>
<td>1375.37-1410.7</td>
<td>109.200</td>
<td>-0.010</td>
<td>-0.008</td>
<td>-0.002</td>
<td>0.182</td>
<td>1.762</td>
<td>-3.938</td>
<td></td>
</tr>
<tr>
<td>1410.7-1970</td>
<td>28.6669</td>
<td>-0.0027</td>
<td>-0.0071</td>
<td>0.0001</td>
<td>-0.2407</td>
<td>3.5067</td>
<td>0</td>
<td>-0.0631</td>
</tr>
<tr>
<td>1970-1996.69</td>
<td>504.4515</td>
<td>-0.0610</td>
<td>-0.1495</td>
<td>0.0006</td>
<td>-0.1711</td>
<td>-2.5533</td>
<td>1.5017</td>
<td></td>
</tr>
<tr>
<td>1996.69-2057.52</td>
<td>-335.5602</td>
<td>0.0280</td>
<td>0.1194</td>
<td>-0.0003</td>
<td>0.0911</td>
<td>-0.2625</td>
<td>0</td>
<td>-0.5695</td>
</tr>
<tr>
<td>2057.52-2060.71</td>
<td>280.3454</td>
<td>0.0438</td>
<td>-0.1892</td>
<td>-0.0008</td>
<td>-0.0461</td>
<td>3.4972</td>
<td>-1.5190</td>
<td></td>
</tr>
<tr>
<td>2060.71-2082.95</td>
<td>-371.2043</td>
<td>0.0371</td>
<td>0.1137</td>
<td>-0.0002</td>
<td>0.5137</td>
<td>-25.3201</td>
<td>0</td>
<td>-0.5001</td>
</tr>
<tr>
<td>2082.95-2218</td>
<td>-77.3583</td>
<td>0.0073</td>
<td>0.0196</td>
<td>0.0004</td>
<td>-0.6479</td>
<td>-3.9719</td>
<td>0</td>
<td>1.0930</td>
</tr>
</tbody>
</table>
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.

6.2 Results of Modelling for the Entire Hole

The values of 'a_{ij}' (Table 3) 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.

6.2.1 Modelled Versus Measured Values for the Entire Well

Figure 5 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.

7. 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 ration 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.

8. 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 be achieved by this.

Since modelling in this paper 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 paper.

References