UTILIZING FIELD DATA TO UNDERSTAND THE EFFECT OF DRILLING PARAMETERS AND MUD RHEOLOGY ON RATE OF PENETRATION IN CARBONATE FORMATIONS

BY

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To my parents, my wife and unborn child

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All praise and thanks be to Almighty Allah, the most Gracious, the most Merciful. Peace and mercy be upon His Prophet.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ROP	:	Rate of Penetration, ft/hr
WOB	:	Weight on Bit, klb_f
RPM	:	Revolutions per Minute
T	:	Torque, klb_f-ft
SPP	:	Stand Pipe Pressure, psi
GPM	:	Gallons per Minute
PV	:	Plastic Viscosity, cp
YP	:	Yield Point, lb/ft^2
HSI	:	Hydraulic horse power per Square Inch, HP/in^2
UCS	:	Unconfined Compressive Strength, psi
$\boldsymbol{\rho}$	:	Density, pcf
$\boldsymbol{\mu}$	:	Funnel Viscosity, 1/sec
%Solids	:	Solid Content, %
$\mathbf{d_b}$	:	Bit Diameter, in
a, b, c	:	Bit Constants

ABSTRACT

Full Name : Ahmad Mohammad Al-AbdulJabbar

Thesis Title : Utilizing Field Data To Understand The Effect of Drilling Parameters and Mud Rheology on Rate of Penetration in Carbonate Formations

Major Field : Petroleum Engineering

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Rate of Penetration (ROP) is defined as the volume of rock removed per unit area (ft) per unit time (hr). This important measurement factor is often captured by many drilling companies to gauge the speed and the efficiency of the time spent to drill a well. They closely monitor it and try their best to increase it as much as possible. It's very challenging to predict ROP values before drilling any well for the purpose of optimization, however, it can be approximated through the use of pure mathematical equations, or using real data to understand the effect of each parameter.

There are several published models to predict ROP values, however, most of them focus on the drilling parameters such as: string revolutions per minute (RPM), weight on bit (WOB), pumping rate (GPM), etc. Only few researchers focused on the effect of mud properties and their influence on ROP values using few or little data, and their results suggested a certain relation of those parameters.

In this research, 7,800 real data point was used to confirm the strong relationship between the rate of penetration and the drilling parameters such as the RPM and WOB. The same behavior was observed with mud parameters especially density and plastic viscosity. The model developed in this research captures the effect of both drilling parameters and mud properties, and showed a strong R^2 value averaging around 0.93 for the three wells.

ملخص الرسالة

الاسم الكامل: أحمد محمد عبدالله العبدالجبار

عنوان الرسالة: استخدام بيانات حقليه حقيقيه لفهم العلاقه بين خصائص الحفر الميكانيكيه والطينيه في التأثير على معدل سرعه الحفر

التخصص: هندسة البترول

تاريخ الدرجة العلمية: ربيع الثاني 1438هـ

يقيس معدل سرعه الحفر كميه الصخور التي يتم ازالتها من البئر بمعدل قدم واحد لكل ساعه. تبرز اهميه هذه القيمه بالنسبه لشركات الحفر في كونها مقياسً لجدوى الاداء اثناء حفر البئر وكم من المده اللتي سوف تستغرق لحفر كامل البئر. على مدى الازمان ، تحاول الكثير من هذه الشركات قياس المعدل الحقيقي لسرعه الحفر او حتى مجرد التنبؤ به ، سواءً باستخدام معادلات رياضيه او باستخدام بيانات حقيقيه سابقه بهدف تقليل التكاليف الكلية التي تصرف لحفر بئر نفطي واحد. عندما نبحث في الكتب او المجلات والاوراق العلميه نجد ان هناك كتاباً تطرقوا لهذا الموضوع لكنهم ركزوا فقط على خصائص الحفر الميكانيكيه دون اخذ الاعتبار للخصائص الطينيه والهيدروليكيه لسائل الحفر. هناك قله من الباحثين الذين تطرقوا للخصائص الطينيه والهيدروليكيه لسائل الحفر ، لكنهم استخدموا عدد قليل جداً من البيانات لاثبات وجهه نظرهم.

في هذا البحث تم استخدام اكثر من 7,800 من بيانات الحفر الحقيقيه للتاكيد على العلاقه القويه بين معدل سرعه الحفر وبين خصائص الحفر الميكانيكيه مثل معدل سرعه دوران انابيب الحفر وكميه الوزن المفروضه على رأس الحفاره. ايضاً تم ملاحظه نفس العلاقه القويه بين معدل سرعه الحفر وبين الخصائص الطينيه والهيدروليكيه مثل كثافه طين الحفر ولزوجته. اخيراً ، المعادله التي تم تطويرها في هذا البحث شملت كلاً من خصائص الحفر الميكانيكيه والطينيه واظهرت معدل خطأ صغير جداً اذا ما تم استخدامها على آبار اخرى لحساب معدل سرعه الحفر. هذا سيفتح المجال لحساب معدل سرعه الحفر قبل حفر اي بئر.

CHAPTER 1

INTRODUCTION

1.1 Importance of Rate of Penetration

Rate of Penetration (ROP) is defined as the volume of rock removed per unit area (ft) per unit time (hr). It also can be referred as the speed of breaking the rock under the bit. In general it measures the speed or the progress of the bit when it drills the formation, and in the field units it is reported in ft/hr. Faster ROP values are always consider good signs since they result in faster delivery of the well and thus saving time and money. However, too fast ROP may result in hole problems and poor hole cleaning that can extend the duration of well delivery and introduce much more complications such as losing part of the BHA in the hole due to formation instability and collapse. As shown in Figure 1, there is clear window where optimum weight on bit and rotary speed will results in a good rate of penetration, while excessive values can lead to poor hole cleaning or downhole vibrations that can cause tool failure. Those values are often set by the bit or BHA provider, or can be calculated based on pure science or based on the feedback from the downhole sensors such as the vibration values, down hole rotation per minute and down hole annular pressure.

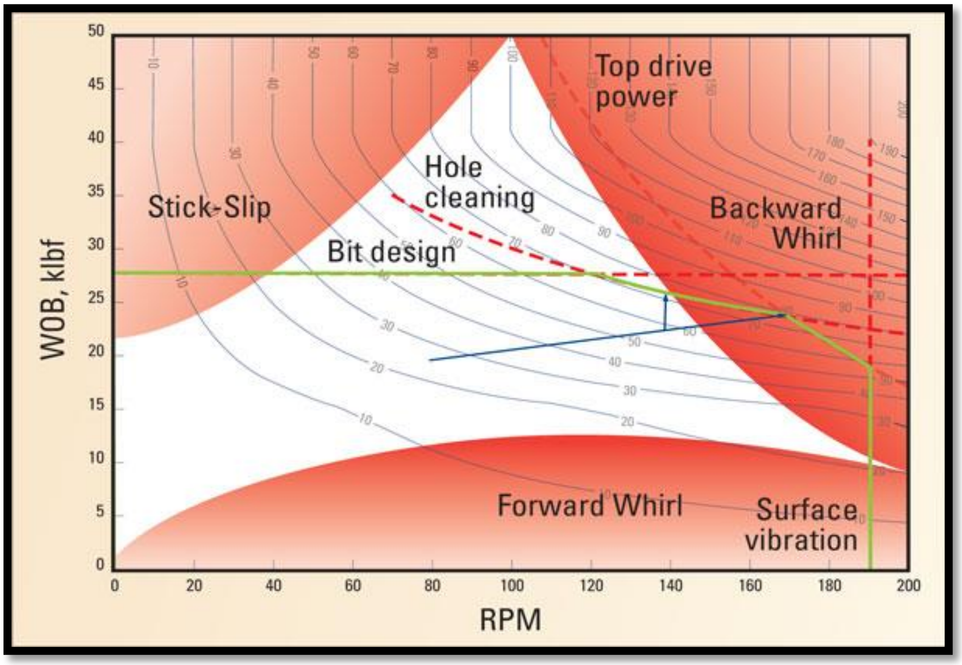

Figure 1: Drilling envelope where balanced WOB and RPM are needed [41]

There are many factors that affect rate of penetration, and one cannot be changed without affecting the other. They are mainly divided into five categories and they are: rig efficiency, formation characteristics, mechanical factors, hydraulic factors and mud properties. The previous five categories, as shown in Table 1, can fall under two general classifications which are controllable factors and uncontrollable factors. Controllable factors are those who can be altered quickly to adjust ROP without impacting the operations economics significantly such as Weight on Bit (WOB), bit design, string Revolutions per Minute (RPM) and hydraulics. Uncontrollable or environmental factors are very hard to change due to economical or geological reasons such as mud weight and type, bit size, overbalance pressure and depth. When it comes to fluid properties and their impact on ROP, it is impossible to change one property without affecting the others, which makes it hard to evaluate the true effect of an individual parameter on the rate of penetration.

Table 1: Factors That Affects Rate of Penetration [17]

Environmental Factors	Controllable Factors (Alterable)
Depth	Bit Wear State
Formation Properties	Bit Design
Mud Type	Weight on Bit
Mud Density	Rotary Speed
Other Mud Properties	Flow Rate
Overbalance Pressure	Bit Hydraulic
Bottom hole Pressure	Bit Nozzle Size
Bit Size	Motor/Turbine Geometry

To drill any well there are three items that needs to be applied in order to create and gain accessibility to the wellbore. The first item is a certain weight applied on the bit. This weight should be high enough to crush and remove the rock, but not too high where the bit gets stuck inside the rock and cannot move, or the bit structure get destroyed. The second item is a rotation mechanics that rotate the bit once it bites the rock so it can grind and detach all the cutting from the rock. Finally, a means of lifting those detached cutting from near-bit area all the way to the surface, as well as cooling the bit and lubricating it. Those three items can be named respectively as weight on bit (WOB), string revolutions per minute (RPM) and pumping rate which is gallon per minute (GPM) in oil field units.

It's worth mentioning that there are two mechanisms for removing the rock volume which are grinding and shearing, see Figure 2. Grinding or crushing is associated with tri-cone bits where the cone teeth bites the rock and crush it before the next teeth arrive and crush the rock layer below it. This works best with hard and brittle rocks where weight on bit is more effective than rotary speed. On the other hand, shearing is the rock removal action of a polycrystalline diamond compact (PDC) bit where high rotary speed is more effective than weight on bit.

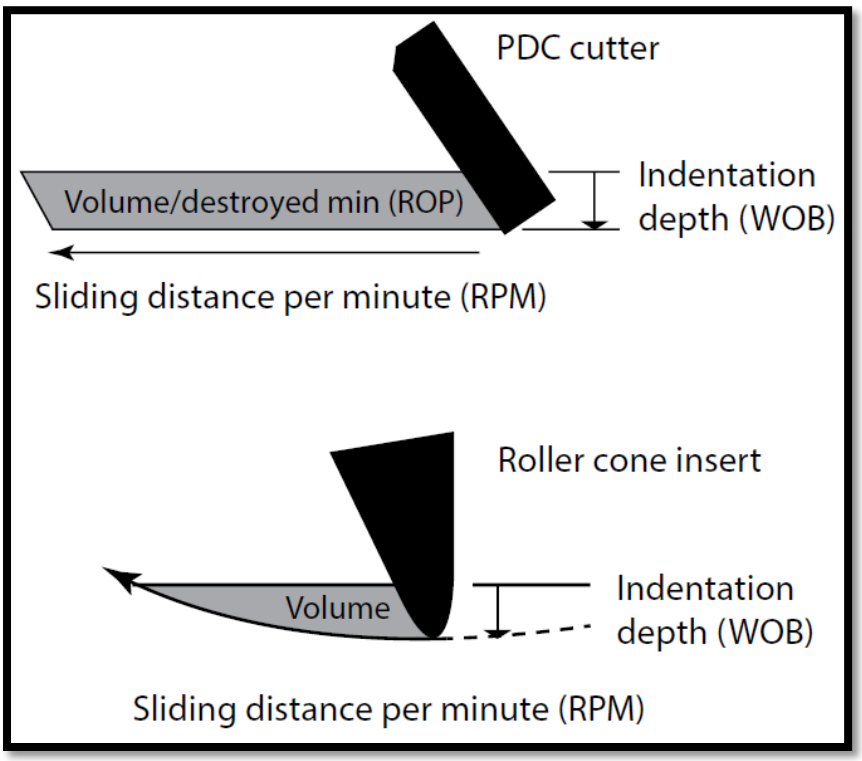

Figure 2: Rock volume removal for PDC bit vs. Tri-cone bit [41]

There are many methods established to understand the effect of drilling parameters and mud properties on rate of penetration. Basic physics and mathematical equations can be used to derive a relationship between them, or the use of current established correlations and linking them together to derive such a relation. On the other hand, real data can be used to validate those relationships and their magnitude, or if they vary linearly or exponentially with the rate of penetration. To date, no solid or reliable model exists due to the complexity of the drilling process, and one cannot capture every factor to predict the rate of penetration. In fact, it was only recent where some authors tried to model PDC bits in their ROP models, and to include directional and horizontal drilling. Adding to that, there is no full model that captures both drilling parameters and mud properties effect on ROP.

1.2 Problem Statement and Research Objectives

Most of the studies in the literature come from theoretical equations and only few authors used real-data to capture the effect of drilling parameters and mud properties on rate of penetration. Also, few researchers focused on the effect of mud properties on rate of penetration, and those who mentioned it used few data, or used semi-analytical models. When surveying through the literature, it was found that some results contradict with each other. For example, Eckel concluded that solid content doesn't affect rate of penetration, while Paiaman confirmed that there was an effect. However, it was not clear in his research if he used real data for solid content, and how many data points were included.

The motive of this research is to understand the effect of drilling parameters and mud properties on rate of penetration from real data point of view. By confirming these effects and whether the results agree with previous works, one can plan ahead of any drilling job to boost the ROP values.

The main objectives of this work are:

1. Understand the effect of drilling and mud parameters on rate of penetration from real data point of view
2. The inclusion of mud properties effects which are rarely present in the literature.
3. Quantify the magnitude of the relationship between rate of penetration and drilling parameters, mud properties
4. Developing a rate of penetration model that captures the effect of both drilling parameters and mud properties

CHAPTER 2

LITERATURE REVIEW

2.1 Drilling Parameters Effect on Rate of Penetration

Maurer (1962) consider the perfect cleaning concept to derived ROP equation for tri-cone bits. He assumed all that all cuttings are removed every time a bit tooth impacts the rocks. His theoretical ROP equation is function of WOB, RPM, bit size and rock strength. His work suggested that ROP varies linearly with RPM and varies with the square of WOB. [28]

$$\boldsymbol{R = k\frac{NW^2}{D^2S^2}} \qquad (2.1)$$

D = bit diameter, in	k = drillability constant	N = rotary speed, RPM
W = weight on bit, lbs	S = strength of rock	R = drilling rate, ft/hr

Galle and Woods (1963) developed a semi-empirical equation, and examined the effect of WOB and RPM values on drilling cost. They investigated the effects of varying WOB and RPM values to achieve the best ROP performance with increased bearing life, while decreasing tooth-wear rate. In their model, RPM was exponentially related to ROP after considering formation type. Also, ROP varies with WOB to the power k which depends also on formation type. Their model was limited to 10,000 lb_f/in of bit diameter. [18]

$$R = C_{fd}\frac{W^k}{a^p}r \tag{2.2}$$

$$r = e^{\frac{-100}{N^2}}N^{0.75} + 0.5N\left(1 - e^{\frac{-100}{N^2}}\right) \qquad \text{(Soft formation)}$$

$$r = e^{\frac{-100}{N^2}}N^{0.48} + 0.2N\left(1 - e^{\frac{-100}{N^2}}\right) \qquad \text{(Hard formation)}$$

Bingham (1965) conducted laboratory studies to develop a rate of penetration equation. He neglected any threshold for the weight on bit and rate of penetration was a function of applied WOB and RPM. He introduced a bit weight exponent (a_5) that can be determined experimentally thus suggesting a non-linear relation between ROP and WOB since WOB is to the power of (a_5). He also suggested a linear relationship with the RPM and ROP. [8]

$$R = K\left(\frac{W}{d_b}\right)^{a5} N \tag{2.3}$$

a_5 = bit weight exponent K = drillability constant

Teale (1965) conducted laboratory experiments and developed a mechanical specific energy (MSE) model, which is the energy needed to drill a volume of rock (Kpsi). He observed that the MSE value was close to the rock compressive strength in psi, thus hinting the bit efficiency. If MSE value is far away from the rock compressive strength, then it means a lot of energy is being lost, and vice versa. [35]

$$\boldsymbol{MSE = \left(\frac{480NT}{d_b^2 ROP}\right) + \left(\frac{4WOB}{\pi d_b^2}\right)} \tag{2.4}$$

d_b = Bit Diameter, in^2 T = Torque, lb-in

Bourgoyne and Young's (1973 and 1974) developed a mathematical model that uses statistical synthesis of the old drilling data to compute some constants that is required for building the full model. There are eight drilling parameters (x_n) and eight unknown exponents (a_n) that require multiple regressions to come up with the best values for these constants. This model is considered to be one of the most important models since it doesn't pre-determine the type of relationship between drilling parameters and ROP. Instead, previous real data governs the type of the relationship. [9]

$$\boldsymbol{\frac{d}{dt}(R) = e^{\left(a_1 + \sum_{i=2}^{8} a_i x_i\right)}} \tag{2.5}$$

$$x_1 = 1.0 \qquad x_2 = 10,000 - TVD \qquad x_3 = TVD^{0.69}(g_p - 9.0)$$

$$x_4 = TVD(g_p - \rho_{ec}) \qquad x_5 = \ln\left\{\frac{\frac{WOB}{d_b} - \left(\frac{WOB}{d_b}\right)_t}{4.0 - \left(\frac{WOB}{d_b}\right)_t}\right\} \qquad x_6 = \ln\frac{N}{100}$$

$$x_7 = -h \qquad x_8 = \ln\left\{\frac{\rho_m}{350\mu d_n}\right\}$$

Warren (1986) derived a perfect-cleaning model for tri-con bits in which cutting removal rate from the bit is equal to the new cutting generation. This means the generation of new cuttings, cutting removal, controls the rate of penetration. The model was modified later on to include chip's hold down effects. His work suggested that ROP is varies non-linearly with RPM and varies with the square of WOB. [38]

$$R = \left[\frac{aS^2 d_b^2}{N^b W^2} + \frac{c}{N d_b}\right]^{-1} \tag{2.6}$$

a, b, c = bit constant S = Confined rock strength

Pessier and Fear (1992) modified Teale equation (1962) by conducting computer simulations and lab tests to introduce the concept of drilling a hole under dynamic conditions where a hydrostatic column of fluid is present. Their Teale modified model includes WOB and RPM which are both linearly dependent on mechanical specific energy. [32]

Hareland et al. (1993) modified Warren ROP model to include the effect of bit wear by introducing a wear function, W_f, into the model. [19]

Osgouei (2007) used Bourgoyne & Young's model as a basis to improve its usage with PDC bits, inclined and horizontal wells. He modified previous parameters to be more suitable for drag bits and directional drilling. Also, he included new parameters such as nozzle diameters, hole cleaning efficiency, mud density and viscosity. [29]

Armenta (2008) modified Teale MSE model to include the effect of bit hydraulics. [5]

$$\boldsymbol{MSE = \frac{WOB}{A_B} + \frac{120\pi \times NT}{A_B \times ROP} - \frac{1{,}980{,}000 \times \lambda \times HP_B}{A_B \times ROP}} \tag{2.7}$$

λ= bit hydraulic factor HP_B = bit hydraulic horse power

Hareland et al. (2010) developed ROP model for tri-cone bits based on laboratory experiments. His model is based on fracturing a rock with one single tri-cone insert. The model is different from others since it was performed using real tri-cone inserts on actual rock which reflects the actual rock fracturing down hole during drilling. His results suggested non-linear relationship between ROP and RPM, WOB. [21]

Khamis (2013) modified Armenta MSE model to modify the of bit hydraulic factor. [23]

$$\boldsymbol{MSE = \frac{4WOB}{\pi d_b^2} + \frac{480\pi \times NT}{d_b^2 \times ROP} - \frac{3{,}189{,}335 \times HP_B}{d_b^4 \times ROP}} \tag{2.8}$$

$\boldsymbol{\lambda}$= $1.2651/d_b^2$

2.2 Mud Properties Effect on Rate of Penetration

Eckel (1954) highlighted that field observations showed ROP drop when a well is drilled with mud compared to water using the same drilling parameters. He conducted laboratory test and concluded that viscosity might play big role in this ROP variation. In addition, it was notice that significant amount of ROP drop occurs if heavy mud is used, and that was confirmed with the use of air drilling where ROP was higher. Also, it was reported that increase in ROP with the use of oil-emulsion mud compared to conventional mud due to the lubrication it adds. During his lab test, he observed increase in ROP with increase in RPM, WOB and GPM. Also, increase in viscosity tends to decrease the ROP until certain point (40 cp) where no further effect is observed. Finally, increasing filtration rate increased ROP and Eckel explained it due to the low viscosity of the high filtrate fluid used. When the data was corrected for viscosity effect, the trend disappeared suggesting a minor effect of filtration on ROP. [13]

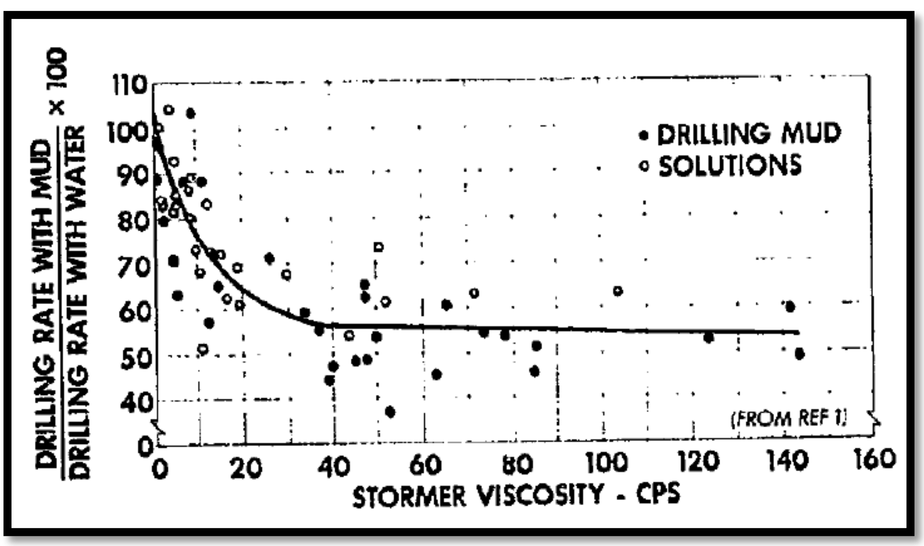

Figure 3: Eckel Exponential Relation for Mud Viscosity vs. ROP [13]

Eckel (1966) reconfirmed that drilling with water is 6-7 times faster than drilling with mud, however, there is no solid answer on why this variation happens. To have better understanding, he conducted laboratory experiment using microbits to drill 10 md limestone. He fixed the WOB and RPM while varying mud properties, flow rate and nozzle diameter. The results showed that at fixed flow rate and nozzle velocity the ROP is a function of kinematic viscosity (viscosity divided by density). Also, Reynolds number is a function of ROP when mud properties and hydraulics are varied, and it increase with ROP increase. Moreover, he stated that for the same kinematic viscosity, ROP is independent of solids content and fluid loss. [14]

Eckel (1968) continued the lab experiment with microbits and this time he altered drilling parameters such as RPM, WOB and differential pressure. He confirmed no changes with the previous relationship between ROP and mud properties which suggest no clear interactions between them. He found that ROP is an exponential function of Reynold number (near bit nozzles). Finally, decrease in differential pressure was suggested to increase ROP, but this wasn't conducted in his experiment. [15]

Beck (1995) tried to link the effects of fluids properties with rate of penetration. He used field data of 8-1/2" hole with 10 ppg mud and all drilling parameters such as RPM, WOB and bit type were constant. He notices 58% increase in ROP with new muds compared to recycled mud which prove the effectiveness of mud properties influence on ROP. As a result he developed an exponential ROP model that takes into account only mud properties changes. He confirmed an increase in ROP with increasing Reynold number values, while a drop in ROP with an increase in plastic viscosity, equivalent bentonite content and Methylene Blue Test (MBT) values. [7]

$$\frac{ROP_2}{ROP_1} = 10^{k(FP_1 - FP_2)} \tag{2.9}$$

k = Regression constant FP = Fluid property

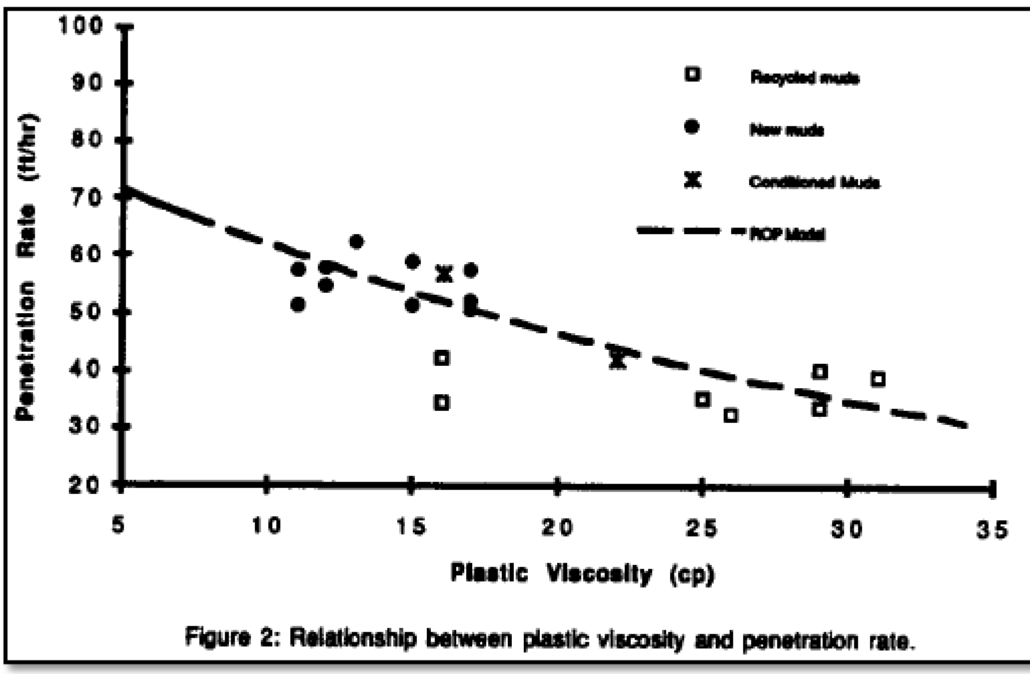

Figure 4: Beck Exponential Relation for Mud Viscosity vs. ROP [7]

Paiaman (2009) investigated the effects of various drilling fluid properties on the rate of penetration. He used field data of 17-1/2" hole then utilized Bourgoyne and Young's ROP model to calculate and normalize ROP values so they don't depend on drilling parameters and it will be easier to alter mud properties and capture all the changes. His results confirmed that ROP decrease with increased mud weight, plastic viscosity and solid content, and they all had liner relationship. He also stated that mud property effects on ROP is not as bad as it was thought, and he linked it strongly with change in formation depth due to compaction and increase in rock compressive strength. [31]

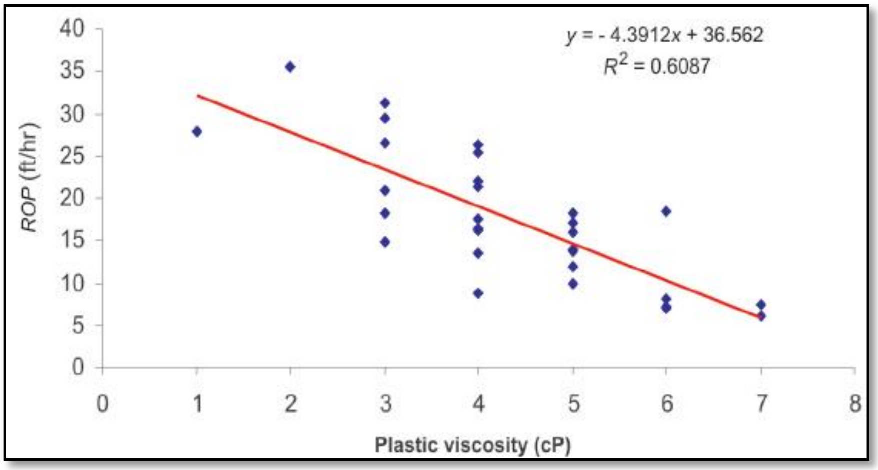

Figure 5: Paiaman Linear Relation for Mud Viscosity vs. ROP [31]

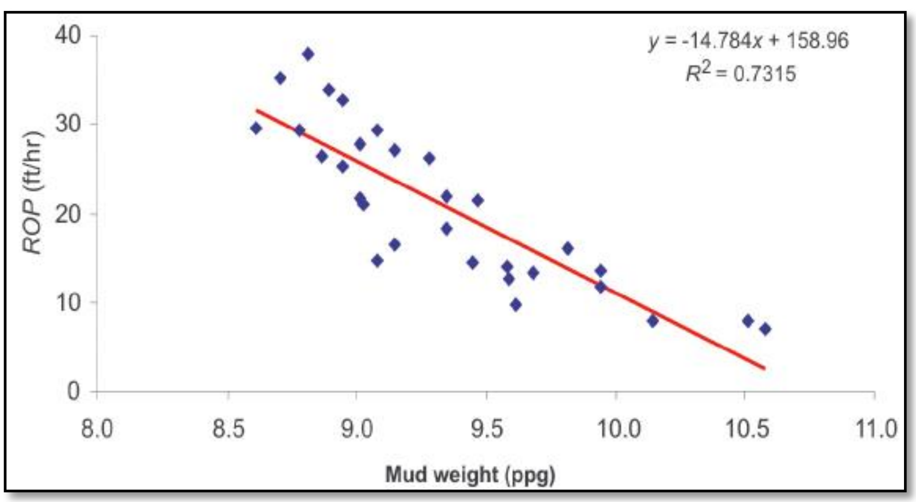

Figure 6: Paiaman Linear Relation for Mud Weight vs. ROP [31]

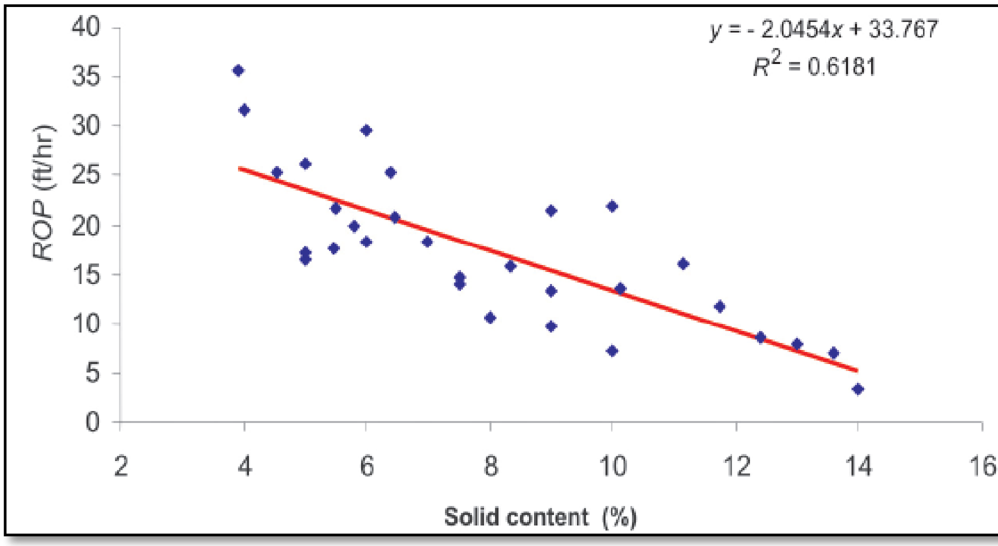

Figure 7: Paiaman Linear Relation for Mud Solid Content vs. ROP [31]

Alum (2011) developed semi-analytical model that relate fluid properties to rate of penetration. Using Bourgoyne and Young's ROP model and real data he generated mathematical equations that relate ROP so mud properties such as plastic viscosity for both laminar and turbulent flows and gel strength. He concluded that even though plastic viscosity and gel strength showed decrease in ROP, yet their net effect is not as significant as they thought to be. The only parameters showed strong relationship with ROP is annular pressure loss since it's directly related to equivalent circulating density, thus any increase in pressure loss will cause a drop to the ROP. The relationship derived from this study was as follows: plastic viscosity, annular pressure loss and differential pressure had exponential relationship with ROP, while it was linear relationship for gel strength. [3]

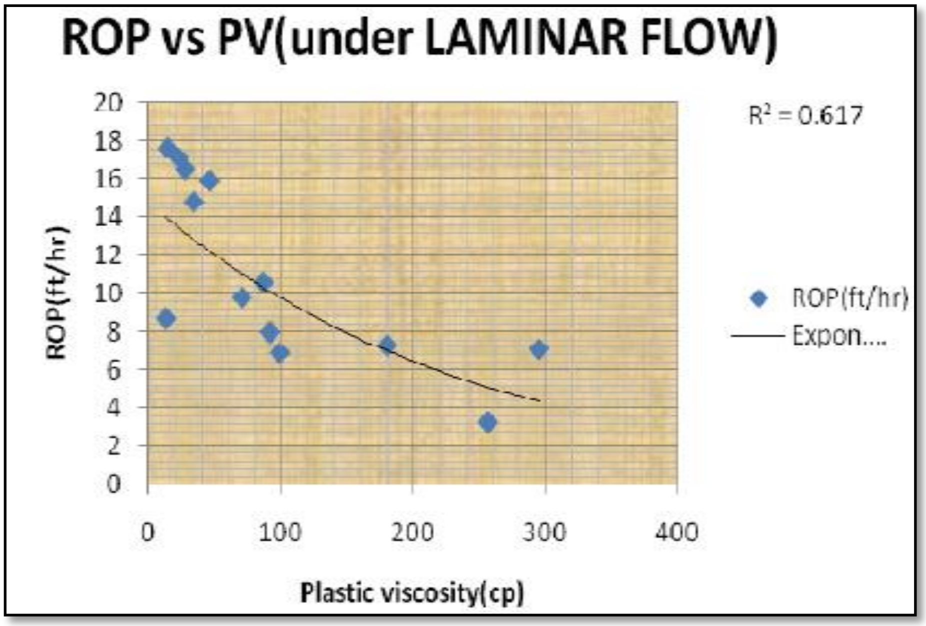

Figure 8: Alum Exponential Relation for Mud Viscosity vs. ROP for Laminar Flow [3]

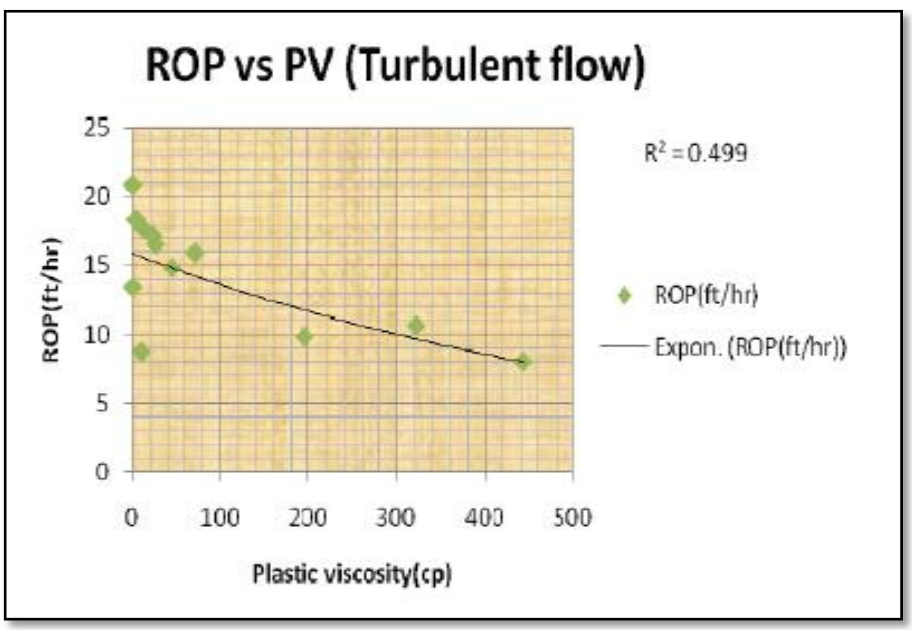

Figure 9: Alum Exponential Relation for Mud Viscosity vs. ROP for Turbulent Flow [3]

Table 2: Summary of Drilling Parametrs and Mud Properties Relation to ROP

Parameter	Author	Effect on ROP
RPM	Maurer	Linear
	Galle and Woods	Exponential
	Bingham	Linear
	Bourgoyne and Young	Nonlinear (RPM^{a6})
	Warren	Nonlinear (RPM^{b})
	Teale	Linear
	Pessier and Fear	Linear
	Hareland	Nonlinear
WOB	Maurer	Square (WOB^2)
	Galle and Woods	Nonlinear (WOB^{k})
	Bingham	Nonlinear (WOB^{a5})
	Bourgoyne and Young	Nonlinear (WOB^{a5})
	Warren	Square (WOB^{2})
	Teale	Linear
	Pessier and Fear	Linear
	Hareland	Nonlinear
Solid Content	Eckel	No relation
	Paiaman	Inverse Relation (Linear)
Viscosity	Eckel	Inverse Relation (Exponential)
	Beck	Inverse Relation (Exponential)
	Paiaman	Inverse Relation (Linear)
	Alum	Inverse Relation (Exponential)
Mud Density	Eckel	Inverse Relation (Field Observation)
	Paiaman	Inverse Relation (Linear)

CHAPTER 3

THEORY

Rate of penetration is influenced by many factors, and before stating the developed rate of penetration model it is best to describe and explained these factors and define them. Most of these factors, especially the mechanical ones, and directly related to the drilling equipment on the rig, and the rig driller have them controlled under his hand. Figures 10 and 11 shows a typical drilling cabin where all the drilling action takes place. Normally a single man, named driller, is assigned alone to take care of the operations happening on the rig floor. However, in larger and more expensive rigs the assistant driller have a secondary chair next to the driller to assist him in all drilling operations especially racking and making up the drill pipes.

Figure 10: Cyber chair with digital control system [41]

Figure 11: Conventional setup with hydraulic control system [41]

For the mud parameters the story is different, and most of the changes are in the hand of the assistant driller and the derrick-man. They are asked to check the mud coming out of the hole and make sure that it is matching the mud program. The mud engineer on location is asked to perform a full mud test twice a day inside his lab and report the results in the drilling daily report.

Figure 12: Mud engineer testing lab on the rig [42]

3.1 Drilling Parameters

3.1.1 Rate of Penetration (ROP)

Rate of Penetration (ROP) is defined as the volume of rock removed per unit area (ft) per unit time (hr). It also can be referred as the speed of breaking the rock under the bit. In general it measures the speed or the progress of the bit when it drills the formation, and in the field units it is reported in ft/hr. Faster ROP values are always consider good signs since they result in faster delivery of the well and thus saving time and money. However, too fast ROP may result in hole problems and poor hole cleaning that can extend the duration of well delivery and introduce much more complications such as loosing part of the BHA in the hole due to formation instability and collapse.

Rate of Penetration is often captured by many drilling companies to gauge the speed and the efficiency of the time spent to drill a well. They closely monitor its values and try their best to increase it as much as possible. It’s very challenging to predict the rate of penetration values before drilling any well for the purpose of optimizing all parameters to push the rate higher. However, it can be done through the use of pure mathematical equations, or using real data to understand the influence of each parameter.

3.1.2 Weight on Bit (WOB)

Weight on Bit is defined as the total force exerted downward on the bit, and it’s reported in klb_f or thousand pounds. Normally, the source of this force comes from the weight of the drill collars. During the Bottom Hole Assembly (BHA) design, 25% of the drill collar weight is usually allocated to keep the string above it in tension and the rest 75% is allocated to be slacked off on the bit to provide the necessary weight on bit. This implies that the maximum weight on bit allowed on the bit is 75% of the drill collar weight, in addition to the bit design limitation. It's not recommended to slack off more than 75% of the drill collar weight since this might cause the pipe above it to buckle, refer to Figure 13 for pipe failure types.

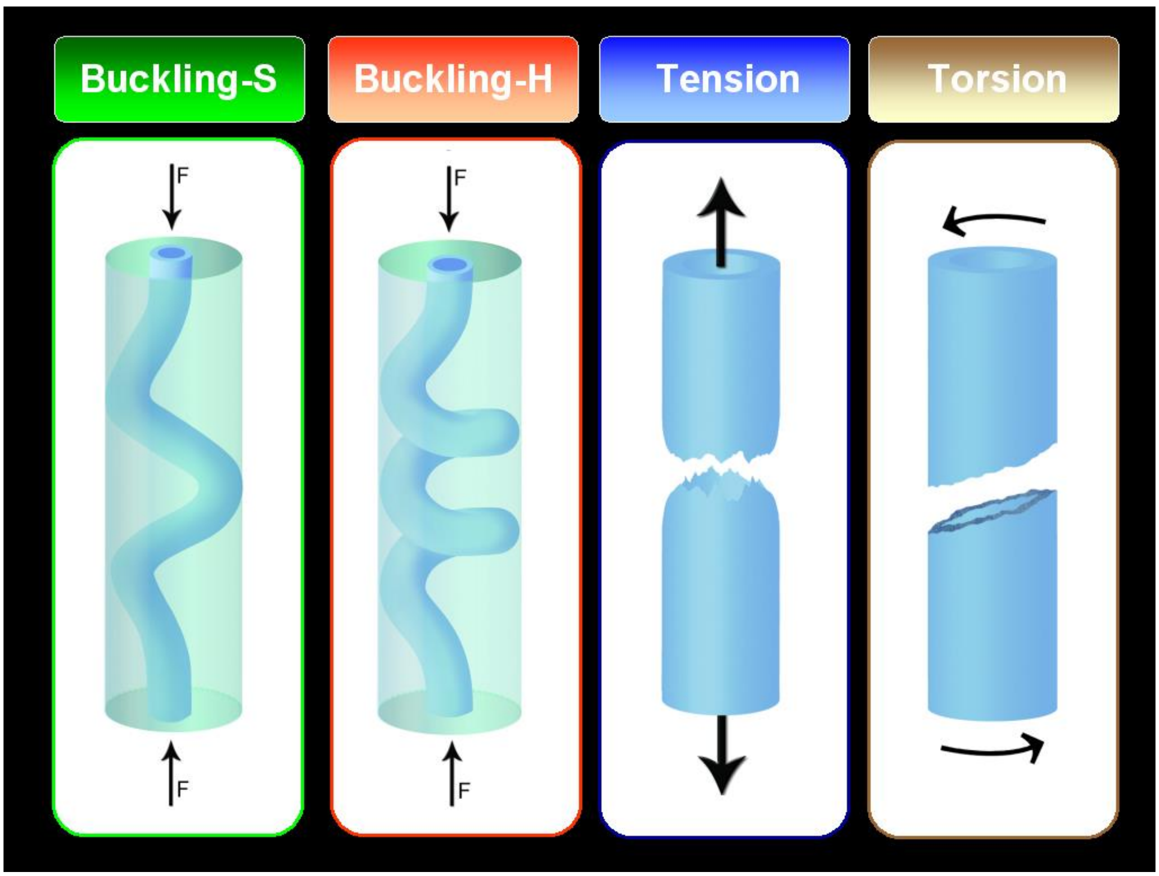

Figure 13: Drill pipe failure types [41]

Weight on bit provides the necessary force for the bit tooth to bite the formation and cause to break. However, too much or little force can cause the rate of penetration to drop significantly. If too much weight on bit is applied, the bit tooth will bite the formation very hard and prevent or reduce the rotation motion. Also, vice versa when little weight on bit is applied causing the bit to rotate and bounce up and down since the force applied is not enough for the bit to bite the formation. The amount of weight on bit can be monitored on the rig floor using the weight indictor, shown in Figure 14. The black arrow indicates the total weight of the string and the red arrow indicates the amount of slacked of weight.

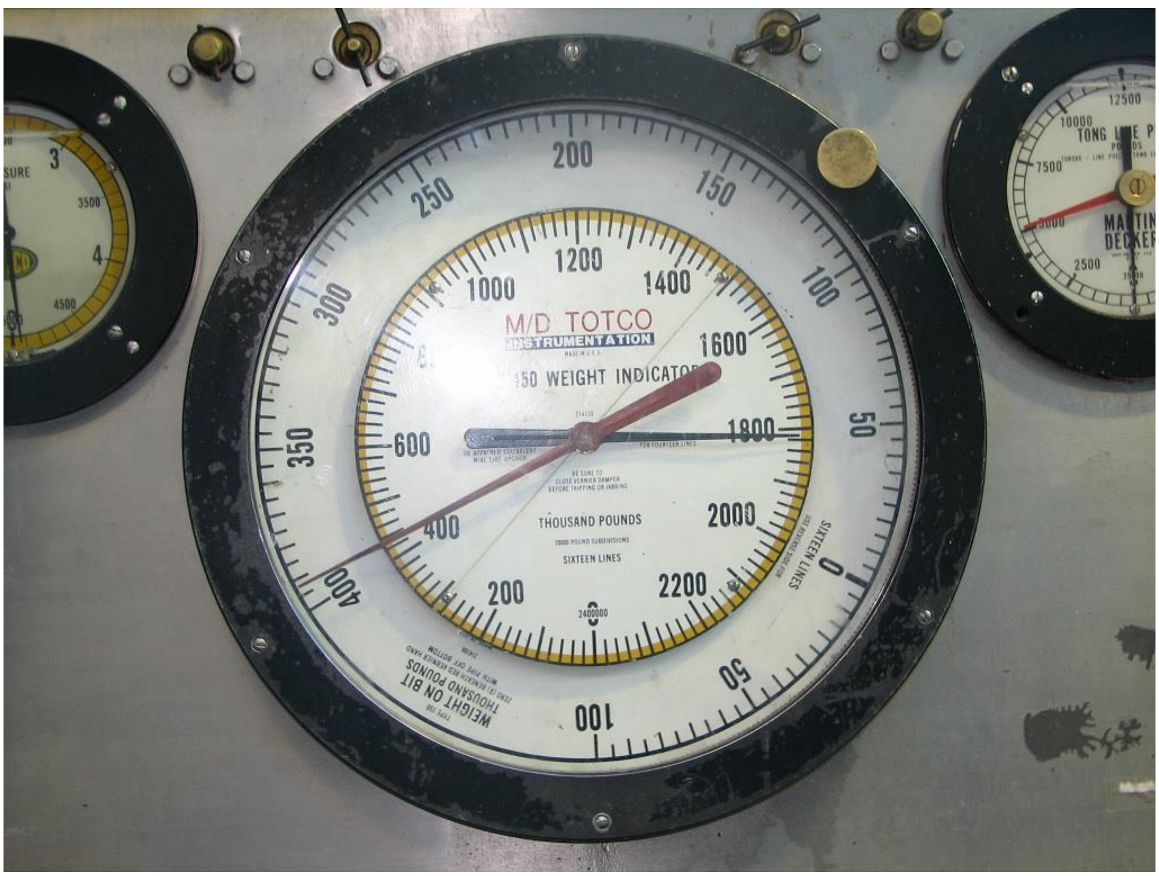

Figure 14: Martin Decker weight indicator [41]

3.1.3 String Rotation Speed (RPM)

String rotation speed or Revolutions per Minute (RPM) measures the frequency of pipe rotation per unit time. Normally, faster pipe rotation yields better and faster rate of penetration, however, just like the weight on bit there is a threshold for it, in which less rotation will not break the rock and faster rotation might cause instability of the bottom hole assembly such as bit whirl and surface vibrations.

There are three sources for the rotational force on the rig, and they are: Top Drive, Kelly and downhole motors. On most rigs, top drive is replacing the Kelly since it provides more power and allows the string to be rotated while pulling out of hole. Downhole motors convers the mud flowing through it to a rotational force through the use of rotators and stators, and they can be used in conjunction with the top drive or Kelly.

Figure 15 : Kelly (upper left), Top Drive (upper right) and Mud Motor (bottom) [41]

3.1.4 Torque (T)

Torque refers to the resistance of drill string to rotate, and it is reported in Klbf-ft. This important parameter reflects and indicates the rock breakage beneath the bit, and higher values of the torque mean more friction and interaction between the bit and the formation. Off course, there is an optimum range for this value otherwise too much energy will be wasted to drill the same amount off rock. Since friction is the main cause of torque, lubricator is used often to reduce it especially when dealing with long sections since high torque values might exceed the pipe tensile strength and cause it to twist off.

3.1.5 Stand Pipe Pressure (SPP)

Stand pipe pressure refers to the total pressure applied from surface, down the bit and back to surface again, and the unit for is psi. This is caused by pressure loss due to the fluid friction which cause pressure drop along the wellbore, thus pressure compensation should be applied from the surface to circulate the mud in and out. The biggest pressure drop usually occurs across the BHA and the bit due to the major ID change out, and in bit hydraulics it is always recommended to allocate 60% of the pressure drop across the bit nozzle. This will enable high jetting force to remove the drilled cuttings and sweep the hole to clean it so the bit won't drill the cutting again.

$$SPP = Drill\ string\ pressure\ loss + BHA\ pressure\ loss + pressure\ loss\ across\ the\ drill\ bit + Annulus\ pressure\ loss$$

3.1.6 Pumping Rate (GPM)

The mud pumping or circulating rate is captured in Gallons per Minute (GPM) and reflects the amount of fluid pumped inside the wellbore. This parameter is strongly related to the stand pipe pressure since more pumping rate yield higher pressure loss. The term Hydraulic horse power per Square Inch (HSI) actually combines both parameters to gauge and measure the energy applied by the bit. Pumping rate can be increased by increasing the number of strokes applied by the mud pumps, or changing the piston size in the mud pump. Higher pumping rates aid in lifting the cutting away from bit so it won't be re-drilled, as well as cleaning the annulus to prevent it from loading thus decreasing the annular friction losses. Too much pumping rate might wash the formation causing instability or losses, or the drill string which creates holes in it and preventing transmitting the mud to bottom.

$$HSI = \frac{SPP \times GPM}{1714} \tag{3.1}$$

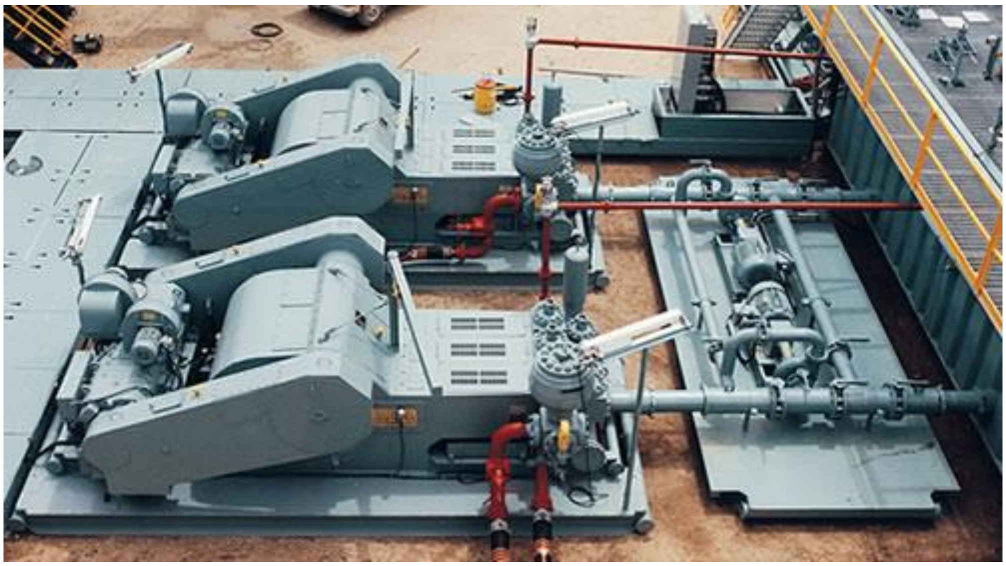

Figure 16: Mud Pump [42]

3.2 Mud Properties

3.2.1 Density (ρ)

The term density quantifies the heaviness of the fluid which is very important parameter in drilling operation since it provided the necessary force to balance the formation pressure, and the unit for it is Pound per Cubic Foot (PCF). It also helps stabilize the formation and increase the wellbore stability. Barite is the main additive used to increase the density of the drilling fluid, and as the density increases many other parameters increase as well such as solid content and viscosity. To measure this important property, a Mud Balance is used which is very convenient and easy to use especially in the field.

Density was said to have an effect on rate of penetration, and many operators noticed that the rate of penetration increase when they drill with water compared with mud. Moreover, one of the solid kick detection methods is rate of penetration increase which means that the well lost its hydrostatic column before it kicked in. This translates to less hydrostatic pressure applied on the formation, and hence less equivalent density.

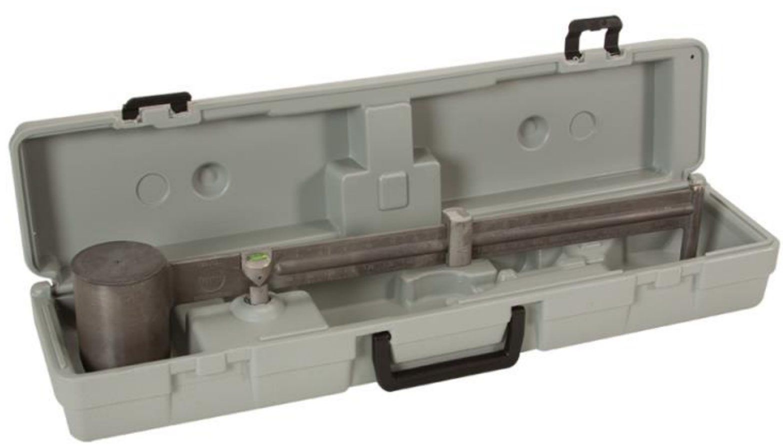

Figure 17: Mud Balance [42]

3.2.2 Funnel Viscosity (μ)

Funnel viscosity measures the resistance of fluid to flow due to shear force resistance between the particles, and the unit for it is 1/sec. It's used to reflect the carrying of the drilling mud and the developed gel strength once the mud becomes static. This is essentially one the important factors affecting hole cleaning and the carrying strength if the mud to lift the cutting all the way to the surface. To measure this property, a Marsh Funnel is used in which it is filled with mud then a timer watch is recording how many seconds it needs for the marsh funnel to be emptied. Higher values of viscosity will make it harder to pump and circulate, but it will improve cutting transportation and suspension. On the other hand, small values of viscosity such as water will not do a good job in cleaning the well, thus high sweeps is open pumped to clean the wellbore. It is worth mentioning that temperature is one of the strongest parameters that affect viscosity, in which higher temperature values will reduce the viscosity. Also, Bentonite is considered the most common source of viscosity in the mud.

Figure 18: Marsh Funnel [42]

3.2.3 Plastic Viscosity (PV)

Even though this term involves viscosity in its naming, however it slight measures a different fluid behavior. The term plastic viscosity reflects the amounts of solids in the mud system, thus the true definition for it is: the resistance of the fluid movement due to shear force resistance between the particles or solids in the mud system, and it is reported in Centipoise (CP). This parameter often reflects the hole cleaning of the well, and the efficiency of the mud cleaning system. It is measured using the viscometer in which two parameters are captures which are 300 RPM and 600 RPM. Once founded, they are subtracted from each other to give the plastic viscosity values.

Figure 19: Viscometer [42]

3.2.4 Solid Content (% Solids)

Solid content is highly related to plastic viscosity since it gives the percent of the solids in the system. Also, it increase with density increase since high density values relay in general on solid content such as the use of hematite or densities above 15 ppg or 110 pcf. To obtain solid content in percentages, Retort Test Skid is used which is shown below.

Figure 20: Retort Test Skid [42]

3.2.5 Yield Point (YP)

Yield point reflects the initial force needed to move the mud due to the positive and negative attraction forces between the mud solids, and the unit for is lb/ft^2. In drilling terminology, it indicates the mud lifting ability of the drilled cuttings. It is also measured using the viscometer in which two parameters are captures which are 300 RPM and 600 RPM. Once founded, the 300 RPM reading is subtracted from the plastic viscosity value.

$$PV = \theta_{600} - \theta_{300} \qquad\qquad YP = \theta_{300} - PV \qquad (3.2)$$

CHAPTER 4

METHODOLOGY

4.1 Proposed Work Plan

Field data will be used for three wells that have the same hole size and formation type. The approach here is to study those real data and conclude if there is a relationship between them or not, and how strong is this relationship. The data will be screened and filtered to capture only drilling properties and mud properties, then they will be plotted against each other to identify the relationship between them. At later stage, the data and the resulting relationships will be used to develop a rate of penetration model that captures the effect of both drilling parameters and mud properties.

4.1.1 Phase I: Collect and screen field data to pick the required parameters.

The below drilling parameters and mud properties will be captured:

- ROP
- Pumping rate (GPM)
- String rotation speed (RPM)
- Torque
- Weight on bit (WOB)
- Stand pipe pressure (SPP)
- Mud density
- Mud funnel viscosity
- Mud plastic viscosity

- Mud solid content in percentage
- Mud yield point

4.1.2 Phase II: Examine the effect of drilling parameters and mud property on ROP.

The data gathered in the first phase will be plotted against the rate of penetration to see if there is any relation between them. The main indicator will be the coefficient of determination (R^2) where higher value indicates a stronger relationship. The results will confirm what previous authors stated and will even quantify the magnitude of the results, or it might disagree with previous findings.

4.1.3 Phase III: Developing ROP model and comparing the results with actual data.

The results will be used to develop a rate of penetration model that captures the effect of both drilling parameters and mud properties. Using the relationships in the second phase, and whether they impact the rate of penetration positively or negatively, the model will be developed with the aid of the real data. Initially, a programing language will be used such as MATLAB or Excel to determine some of the constant in the equation, if any, and later on confirm the relation type between the rate of penetration and the inputs. Once done, the model should be able to predict future ROP values, and that where the comparison will take place to validate if its prediction is correct or not.

4.2 Least Square Method

Least square method is one of the popular and most important approaches when performing any regression analysis. The term least square requires minimizing the summation of the square of the error in the results of any equation. This ensures that most data on the chart are nearly fitted with a line passing through most of them. Correlation Coefficient (R) measures the strength and relation between two data sets plotted on the X and Y chart, and closer this value to 1 the stronger the relationship. On the other hand, Coefficient of Determination (R^2) gauges the strength of how can one variable be predicted by the other. The closer this value to 1 the stronger the prediction. One of the easiest applications to use is Excel, it offers friendly interface and quick to use layout.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \tag{4.1}$$

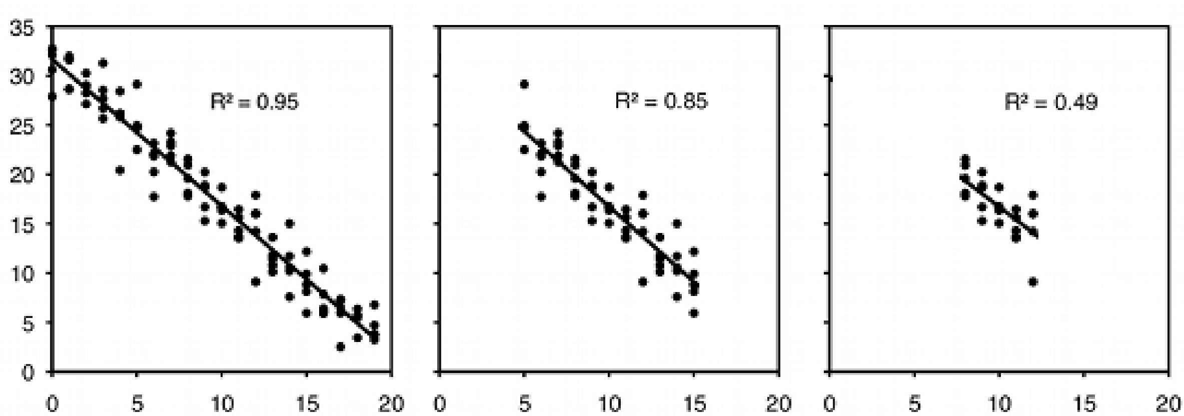

Figure 21: Example of different R^2 values [40]

4.3 Non-Linear Regression

Non-linear regression involves the use of non-linear combination models that depends on one or more independent parameters. It is best used with equations involving more than one parameter such as the rate of penetration, or data fitting that have a high curvature in it making it non-linear. If linear relation is applied compared to non-linear, the relationship will suffer from high errors and deviations from the original dataset. In this research I'll be using XLSTAT which is a small plug-in for Excel that performs various types of regression analysis, and later on in Chapter 5 they will some demonstration for it.

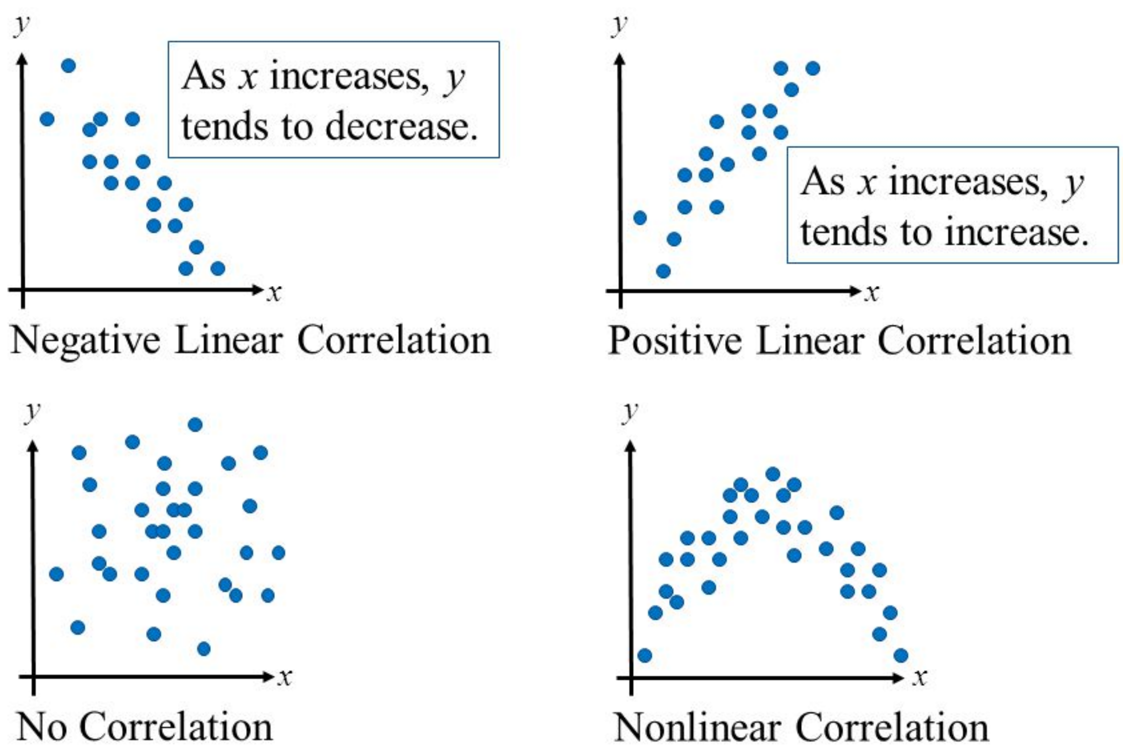

Figure 22: Types of correlations [40]

CHAPTER 5

RESULTS AND CONCLUSION

This chapter will go over all steps performed to obtain the rate of penetration model and how drilling parameters and mud rheology relates and affects the rate of penetration. The field chosen in this study was in offshore for a reason which is the consistency in the operation. Most of the new offshore rigs have cyber capabilities in which robots and automated systems are used to make up the drill pipes and drop the slips. This will ensure that the connection-to-connection speed stays on average value, thus ultimately impacting the average daily rate of penetration value. The same rig will be used to keep the correlation as accurate as possible. Also, the same bit type was used on these wells which is seven bladed PDC bit.

Just like what the methodology mentioned, the first part here will cover the data screening and filtering, while the second part will show how the relationship between rate of penetration and other parameters were obtained, and finally in the last part all steps will be shown on how the model was derived. The model will be derived based on one well and then will be tested on two others.

5.1 Overview of the Data Used

Three wells were selected in an offshore field with depth ranging from 5,000’ to 9,000’. This interval is known for its many carbonate formations. All wells are nearly vertical and conventional Bottom Hole Assembly (BHA) was used. The size of the hole section is 16” which implies that this is an intermediate section, and the target entry is not a reservoir yet. The formation lithology and Unconfined Compressive Strength (UCS) is mention below in Figure 23. The first well encountered thinner layers which made the section drilling very fast, while the third well encountered thicker layers. Total of four layers were present in this hole section, and no major wellbore issue were encountered. The total number of data point used in this research (several parameters at a certain given depth) is around 7,800 and the number of overall data exceeds 40,000.

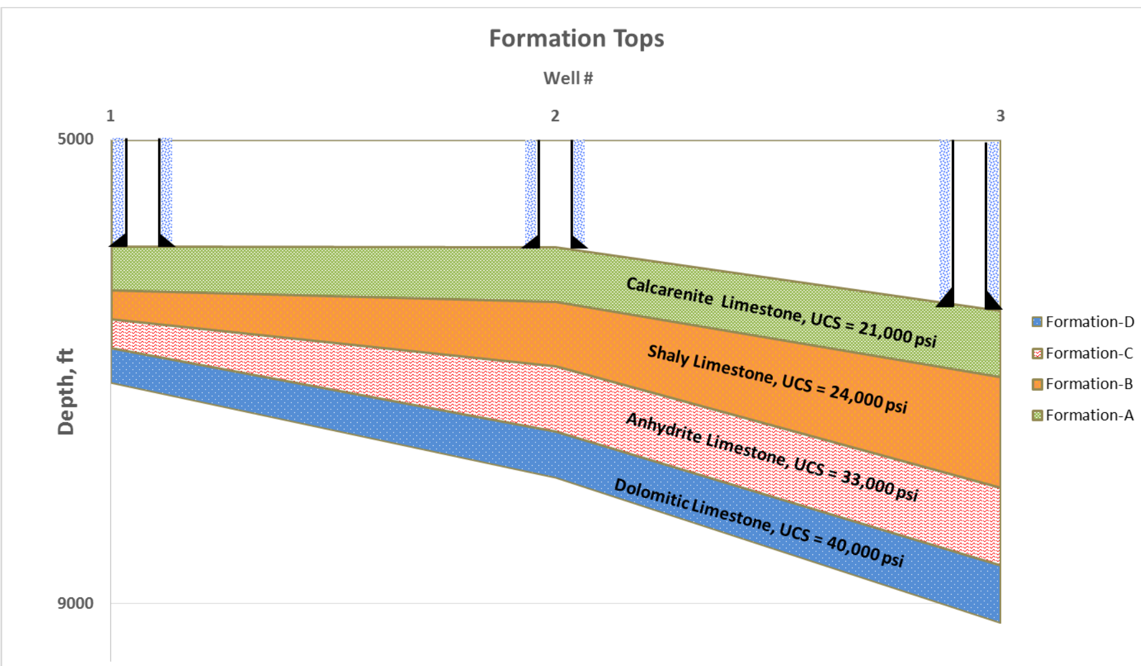

Figure 23: Formation tops and wells location

5.1.1 Data Gathering and Screening

The data was taken from a real-time sensor, and most of them were captures on a footage based. This implies that the number of data points will be close to the number of section footage. Initially, this data will include all sorts of operations done on the 16" hole section including drilling, tripping and running casing.

The first step was only to capture the part where new footage was made and discard the rest. This requires human interface using data filtering and elimination. What was done is the following:

Figure 24: Data filtering process

This implies that if the current footage was 1,000 then suddenly the depth logs shows 930' then it is a trip out of the hole. At the end, only drilling data will be present in the data set and they are divided into the following:

Table 3: Layout of drilling parameters filtered data

Depth, ft	ROP, ft/hr	GPM	RPM	WOB, Klb_f	Torque, Klb_f-ft	SPP, psi	Bit Size, in

5.1.2 Mud Properties Data

The challenge with mud properties is their quantity. Mud properties are captured daily on the daily report and they are not instantaneously measure in real-time, at least not with today's technologies. This can be challenge since there will be only few data present in each section. If one hole section takes two days to drill, then there will be only two data point for mud properties that is obtained from the daily report. Luckily, in our data set the mud properties were captures twice a day with 12 hrs separation, thus doubling the number of data set. To overcome the data quantity limitation, the data of the entire field was used to bring the number of the data set to as high as 500 data point.

Another challenge that arises is the nature of capturing these properties. What happens is that every daily report mentions the mud properties along with the daily average rate of penetration. This does not capture the effect of any mud property change over any instantaneous rate of penetration value. However, the effect between ROP and mud properties can still be observed if the entire field data is taken. In the future if technology allows, maybe it will be possible to perform this if sensors were installed in the mud flowline and recorded the data instantaneously. The order at which these properties where captured is below:

Table 4: Layout of mud properties filtered data

Viscosity, sec^{-1}	**YP, lb/ft^2**	**PV, cp**	**Solids %**	**Density, pcf**	**ROP, ft/hr**

5.2 Drilling Parameters Effect on ROP

After preparing only the drilling data, they ware plotted against the rate of penetration. Two things will be captures here which are relation type and the coefficient of determination (R^2). Microsoft Excel will be used to plot the data and find the relation type and R^2 between the data set. All the results for the three wells will be presented in the below sections.

5.2.1 Weight on Bit (WOB)

Weight on Bit is defined as the total force exerted downward on the bit, and it's reported in klb_f or thousand pounds. It can be understood logically that more weight applied on the bit will boost the penetration rate, however, the magnitude of that effect and the relation type might be different. When weight on bit was plotted with rate of penetration for all three wells as shown in Figures 25-27 it became clear that the relation is somehow liner and there is a strong relationship between them. The average correlation coefficient R is 85% which suggest a strong relationship, and the coefficient of determination R^2 is 72% on average implying that weight on bit can be part of the rate of penetration model.

Looking at the three plots, one can say the following:

- The data density increases as moving toward the last well. This is true since the section thickness increases as shown in Figure 23, and this is true for the rest of the drilling parameters.

- Weight of bit threshold can be seen in Figures 25 and 26 for each specific well. In the first one, it is clear that the rate of penetration wasn't responding until the weight on bit exceeded the value of 13 Klb_f which hints the value needed to break the rock using those parameters. This means that the rock would have broken easier with less force if the hydraulics were more optimized for example. It is only at those conditions were the rock didn't break quickly with a force below 13 Klb_f. The same applies to the Figure 26 where weight on bit above 33 Klb_f was not sufficient since other parameters were not optimized. It will be seen later that hydraulics were increased in Well-C, that's why higher weight on bit values were possible to achieve.

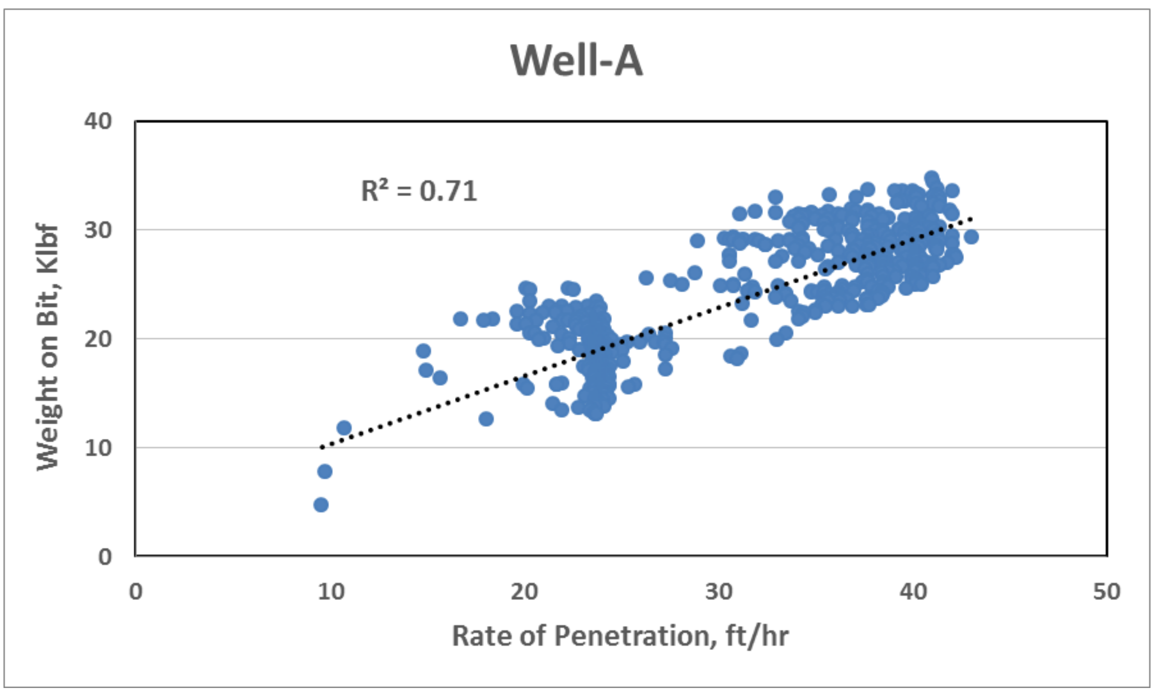

Figure 25: WOB vs. ROP for Well-A

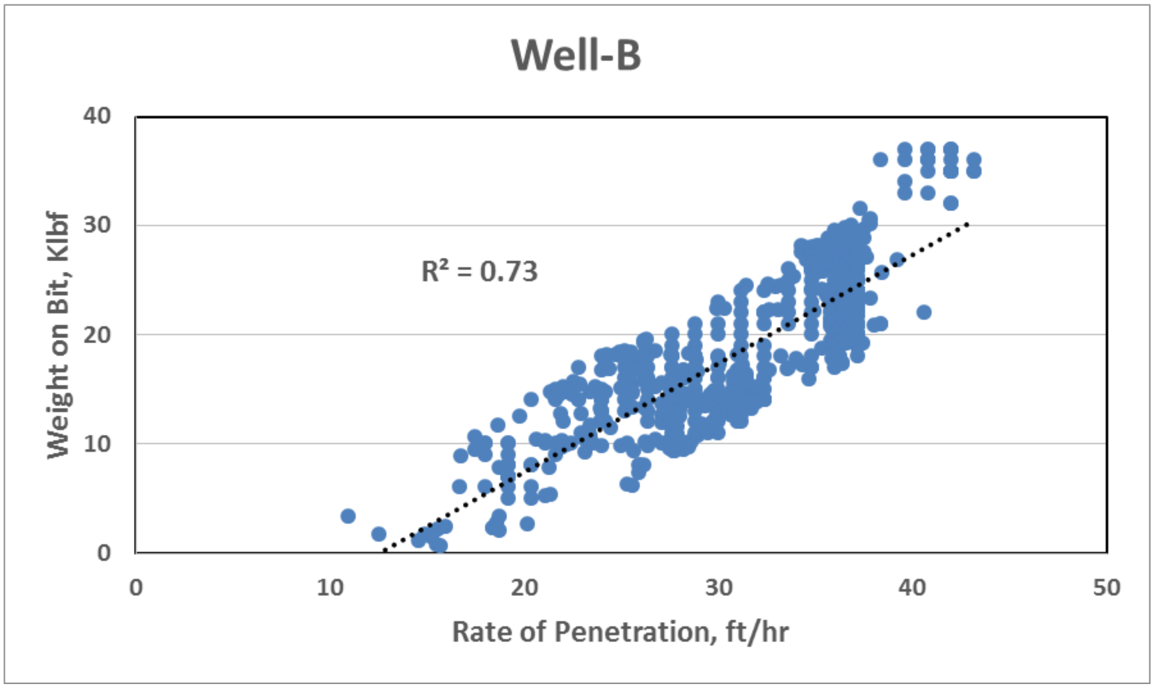

Figure 26: WOB vs. ROP for Well-B

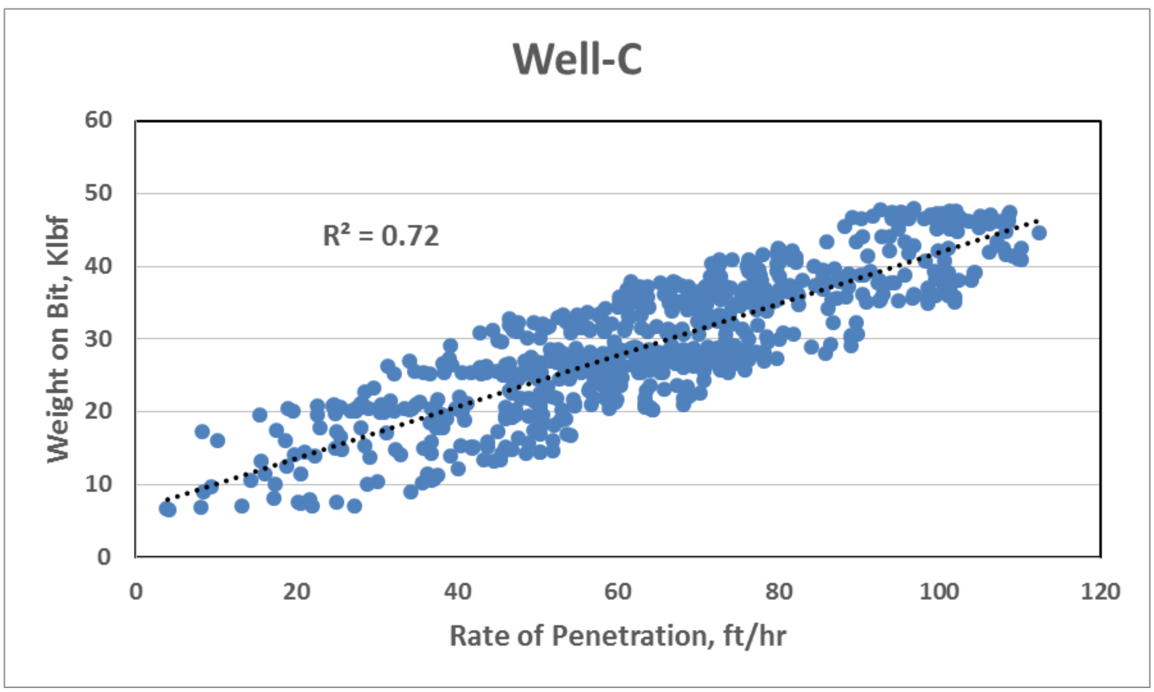

Figure 27: WOB vs. ROP for Well-C

5.2.2 String Rotation Speed (RPM)

String rotation speed or Revolutions per Minute (RPM) measures the frequency of pipe rotation per unit time. Higher rotation speed doesn't guarantee higher penetration rates since it can introduce vibrations and unwanted mechanical instability that cause wellbore stability problems and may end up in losing the entire drilled hole. When string rotation speed is plotted against the rate of penetration for all three wells as shown in Figures 28-30 it became clear that the relation is purely liner and there is a strong relationship between them. The average correlation coefficient R is 89% which suggest a strong relationship, and the coefficient of determination R^2 is 80% on average implying that string rotation speed can be a part of the rate of penetration model.

It can be concluded from the three plots that high string rotation rates doesn't mean high penetration rates, and this can be seen clear in well-A and well-C. In well-A the rotation speed reached around 200 rev/min while the max rate of penetration was close to 45 ft/hr. On the other hand in well-C the rate of penetration was touching 120 ft/hr with only 130 rev/min. This strongly ensures that other parameters need to be optimized in order to bring the penetration rate higher. The deeper the bit goes the higher the rotation needed to transmit it to bottom, also the softer the formation encountered the higher the rotation can be, and this explains the steps or ladder shape on the three graphs. It's worth mentioning that PDC type bit responds higher to RPM compared to tri-cone bit where WOB is more favorable. This is related to the bit butting mechanism where in PDC bit it called shearing and in tri-cone bit it called crushing.

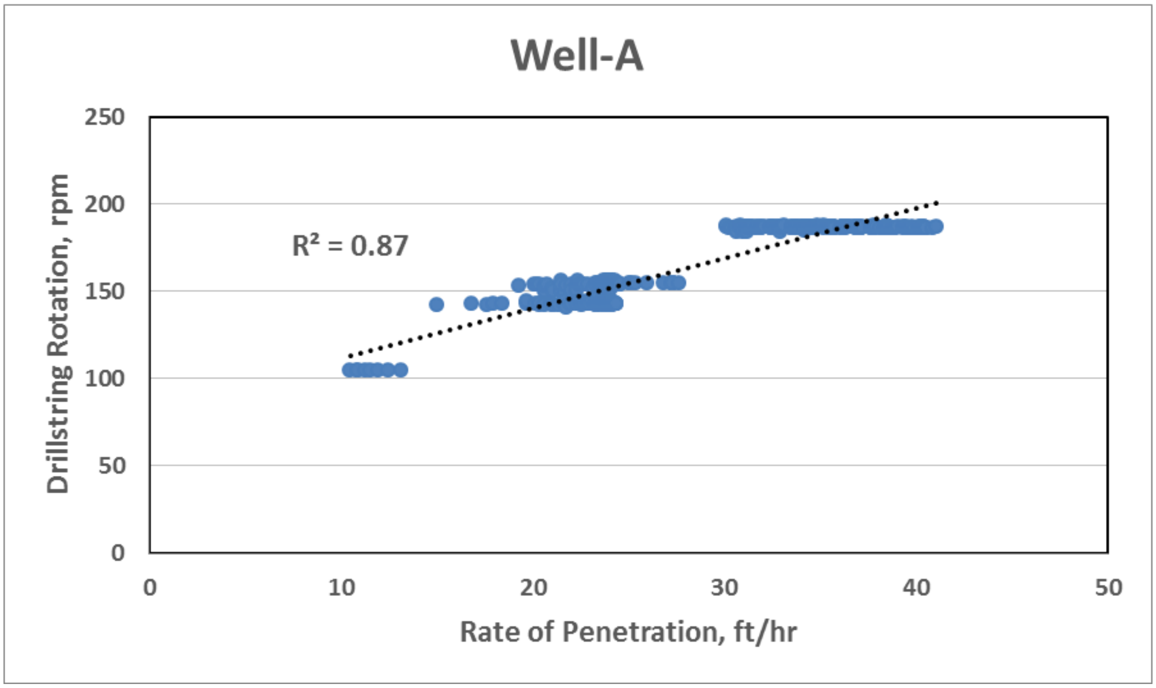

Figure 28: RPM vs. ROP for Well-A

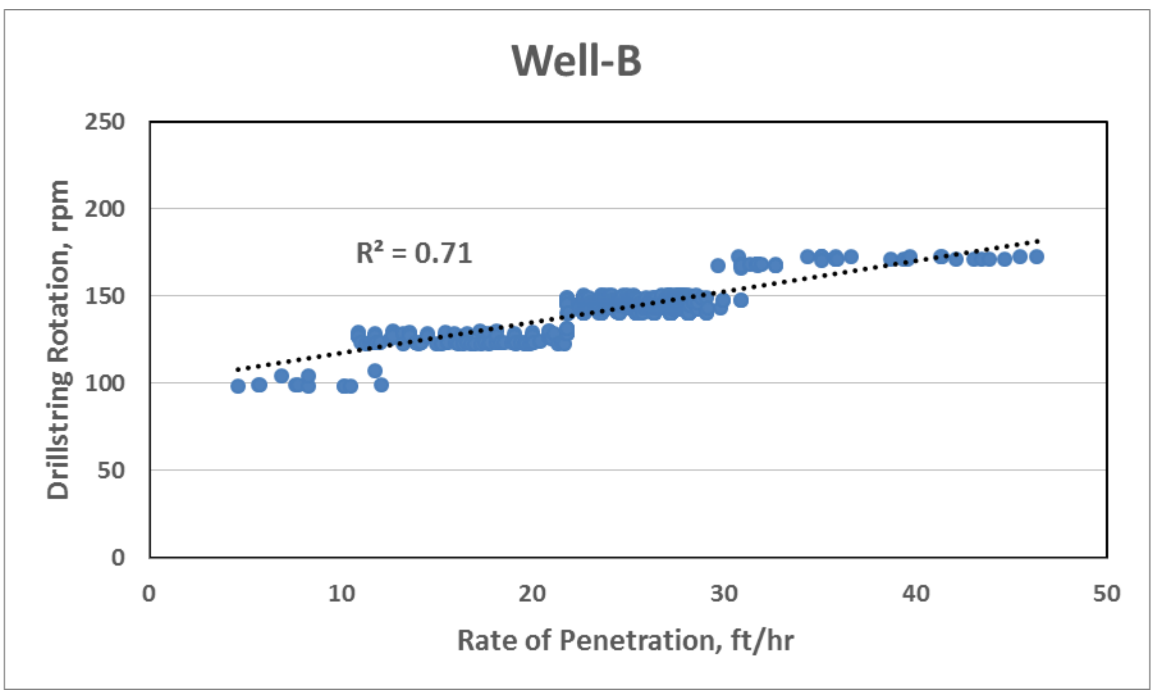

Figure 29: RPM vs. ROP for Well-B

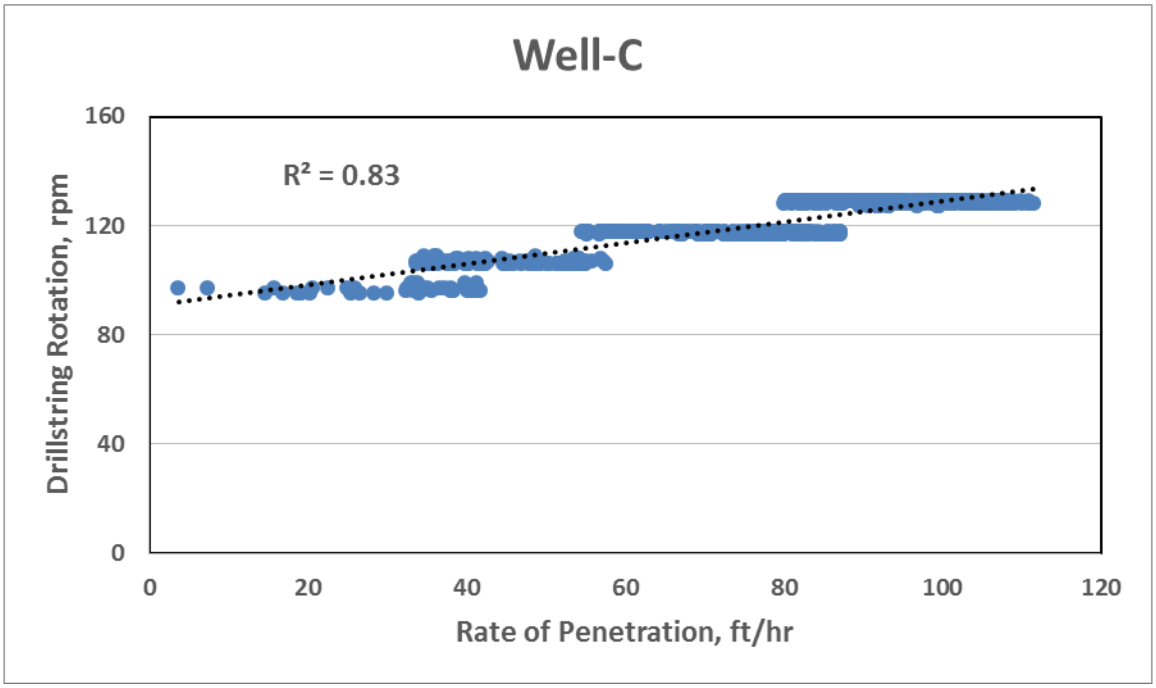

Figure 30: RPM vs. ROP for Well-C

5.2.3 Torque (T)

Torque refers to the resistance of drill string to rotate, and it is reported in Klbf-ft. It can indicate positive engagement and rotation between the bit and formation, however, very high values can lead to a serious damage in surface and bottom hole equipment. Since mud properties play a major role in reducing high torque values using the lubrication property, the torque value itself can be used to gauge the efficiency of the mud properties such as hole cleaning, solids amount and lubrication. When drilling torque is plotted against the rate of penetration for all three wells as shown in Figures 30-33 it became clear that the relation is purely liner and there is a strong relationship between them. The average correlation coefficient R is 85% which suggest a strong relationship, and the coefficient of determination R^2 is 72% on average implying that drilling torque can be a part of the rate of penetration model.

It becomes very clear from the three plots below that higher penetration rates require higher torque values. Even though well-A has the highest RPM values, yet it recorded the lowest range of torque values and vice versa with well-C. This ensures that higher rotational speed doesn't always increase the torque number, and instead it is the combination of all other parameters, especially the weight on bit.

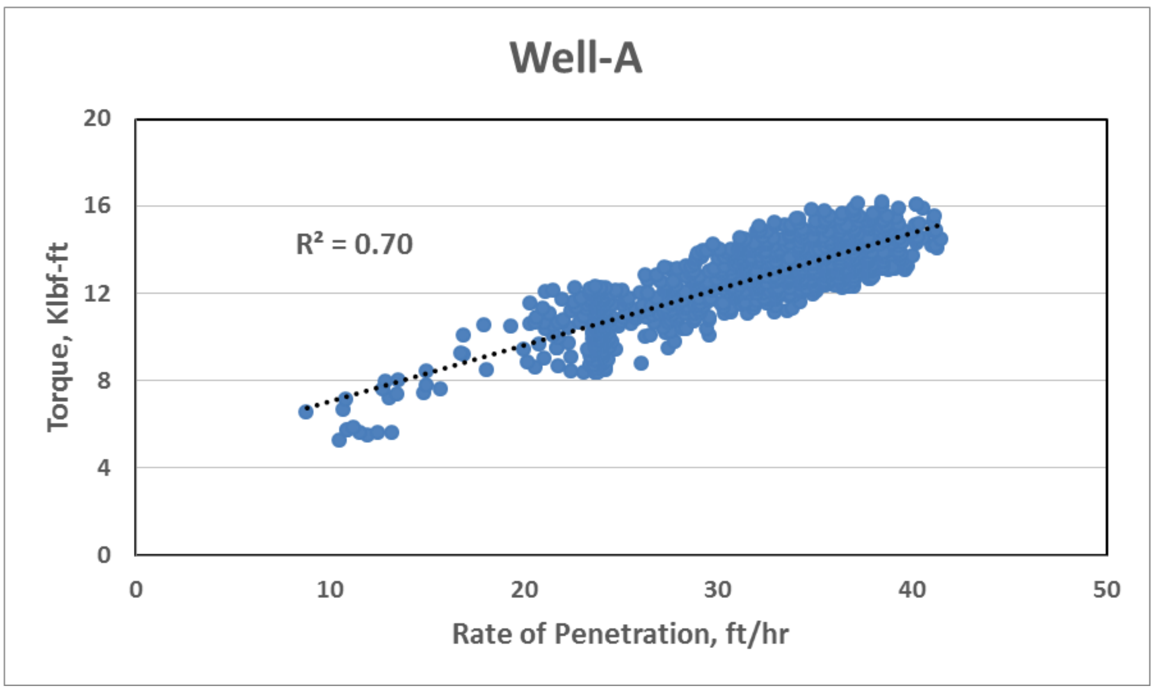

Figure 31: Torque vs. ROP for Well-A

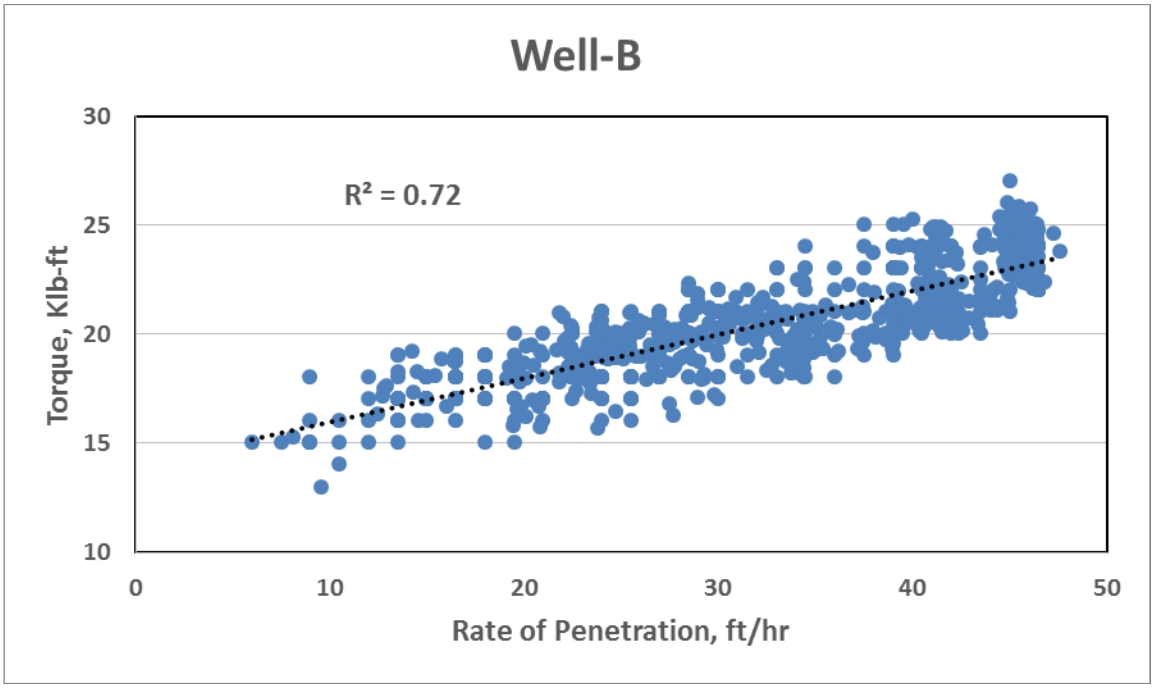

Figure 32: Torque vs. ROP for Well-B

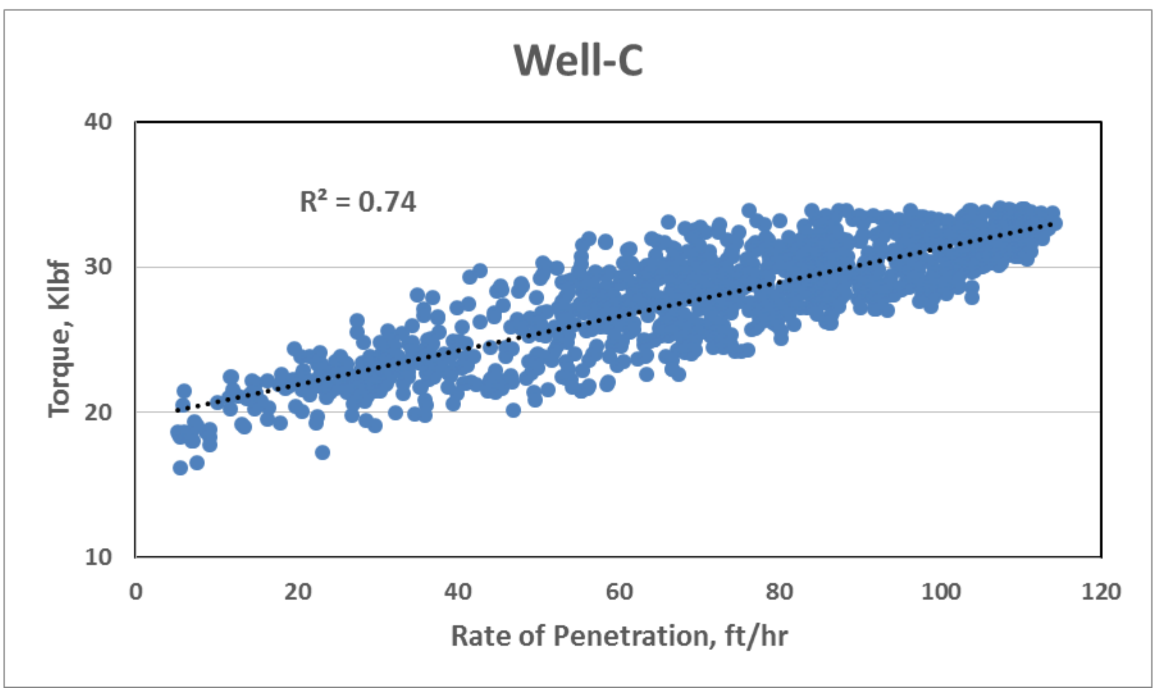

Figure 33: Torque vs. ROP for Well-C

5.2.4 Stand Pipe Pressure (SPP)

Stand pipe pressure refers to the total pressure applied from surface, down the bit and back to surface again, and the unit for is psi. This essential parameter, alone with GPM, defines the basic hydraulics applied to the entire drilling system. In conjunction with pumping rate, it aids in selecting the optimum nozzle sizes for the best hydraulic and jet impact. Sometimes it can even help in determining the pumping rate value itself. It tends to change with mud properties such as density and solid content or with depth where it will increase due to more friction encountered.

When standpipe pressure is plotted against the rate of penetration for all three wells as shown in Figures 34-36 it became clear that the relation is purely liner and there is a strong relationship between them. The average correlation coefficient R is 87% which suggest a strong relationship, and the coefficient of determination R^2 is 75% on average implying that standpipe pressure can be a part of the rate of penetration model.

From the three graphs below, it can be seen that in general higher rate of penetration values requires higher optimized hydraulics. This will become clear once the HSI is obtained in few pages. Well-C shows higher pressure values at even low ROP values which hint the optimization done on this well to reach the +100 ft/hr penetration rate.

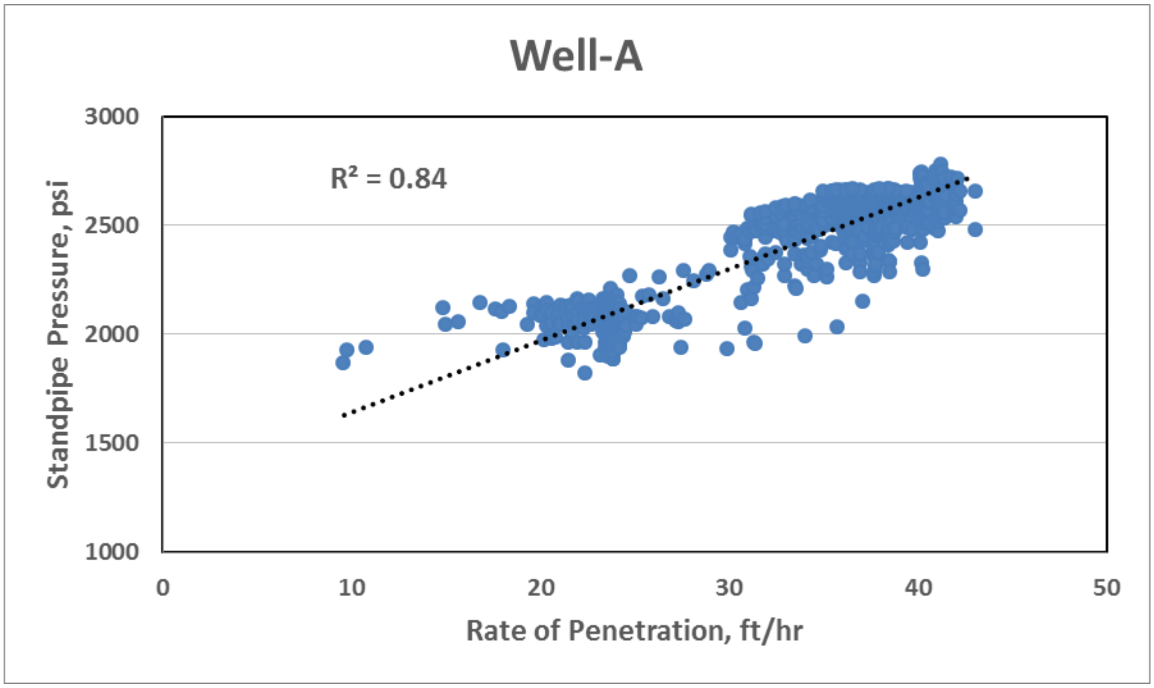

Figure 34: SPP vs. ROP for Well-A

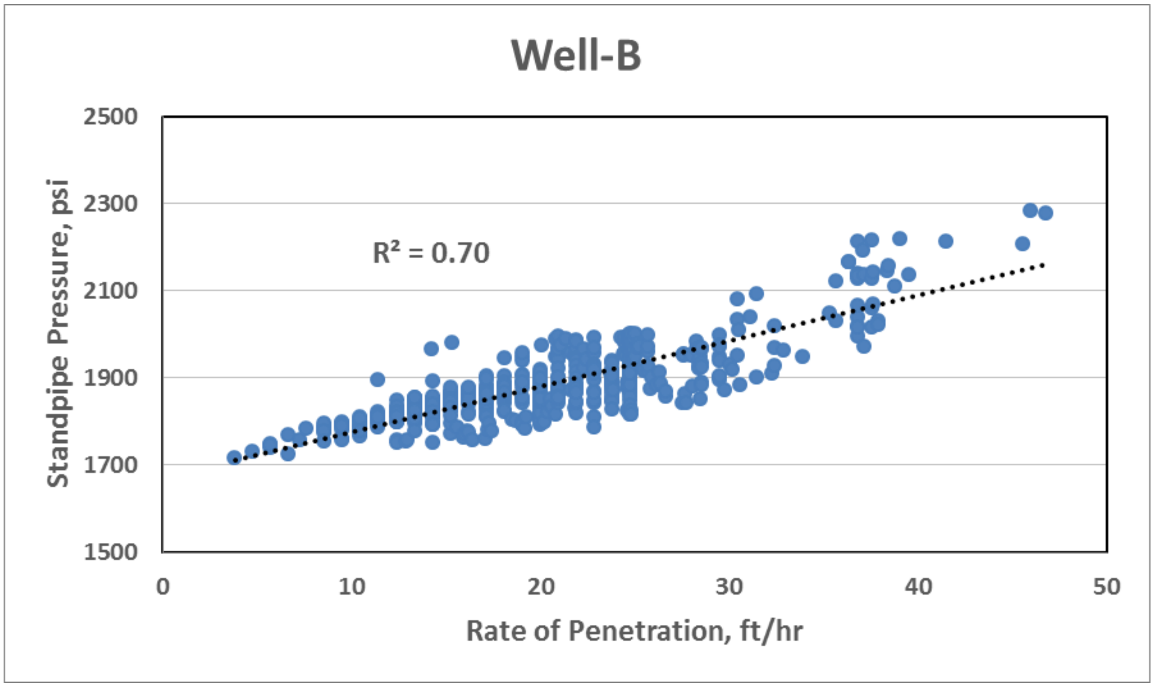

Figure 35: SPP vs. ROP for Well-B

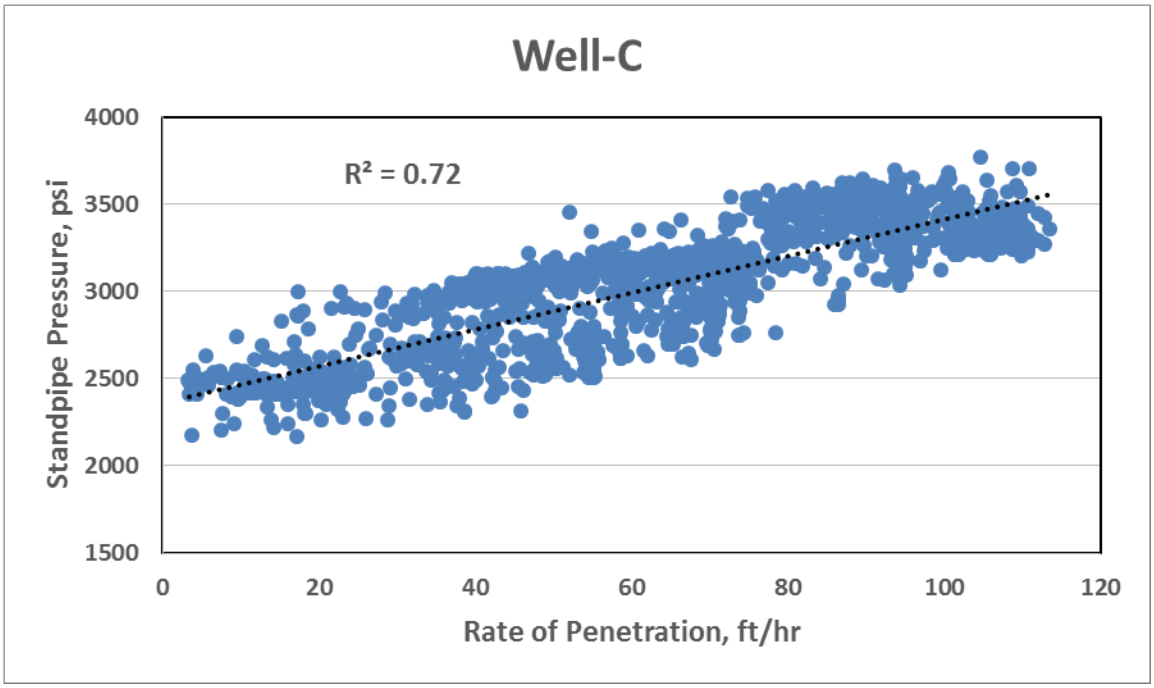

Figure 36: SPP vs. ROP for Well-C

5.2.5 Pumping Rate (GPM)

The mud pumping or circulating rate is captured in Gallons per Minute (GPM) and reflects the amount of fluid pumped inside the wellbore. This parameter is strongly related to the stand pipe pressure since more pumping rate yield higher pressure loss. Excessive pumping rate can washout the wellbore or the drilling string especially when the mud contains high solids. On the other hand, pumping rate improves the hole cleaning efficiency and the hydraulics around the bit since it delivers more fluid to it. When pumping rate is plotted against the rate of penetration for all three wells as shown in Figures 37-39 it became clear that the relation is purely liner and there is a strong relationship between them. The average correlation coefficient R is 92% which suggest a very strong relationship, and the coefficient of determination R^2 is 84% on average implying that pumping rate should be a strong part of the rate of penetration model.

It can been seen from the three plot below with do doubt that higher pumping rate increase the rate of penetration, and this is due to the hydraulics transferred to the bit and to the amount of the hydraulic impact applied. Since the section length in well-C is longer, it was possible to attain 1,100 GPM at a longer period, while in well-B it was only for a shorter period of time. The deeper the bit goes the higher rate is needed to maintain the same hydraulics, also the softer the formation encountered the higher the pumping can be applied to remove the cuttings as quickly as possible, and this explains the steps or ladder shape on the three graphs.

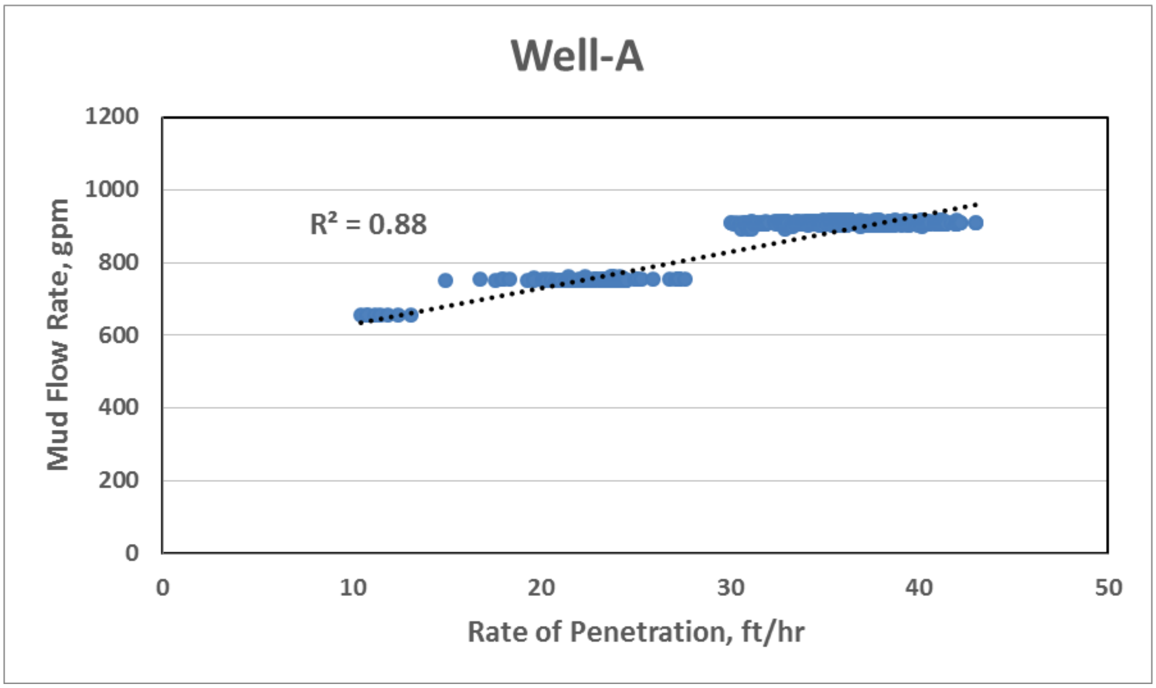

Figure 37: GPM vs. ROP for Well-A

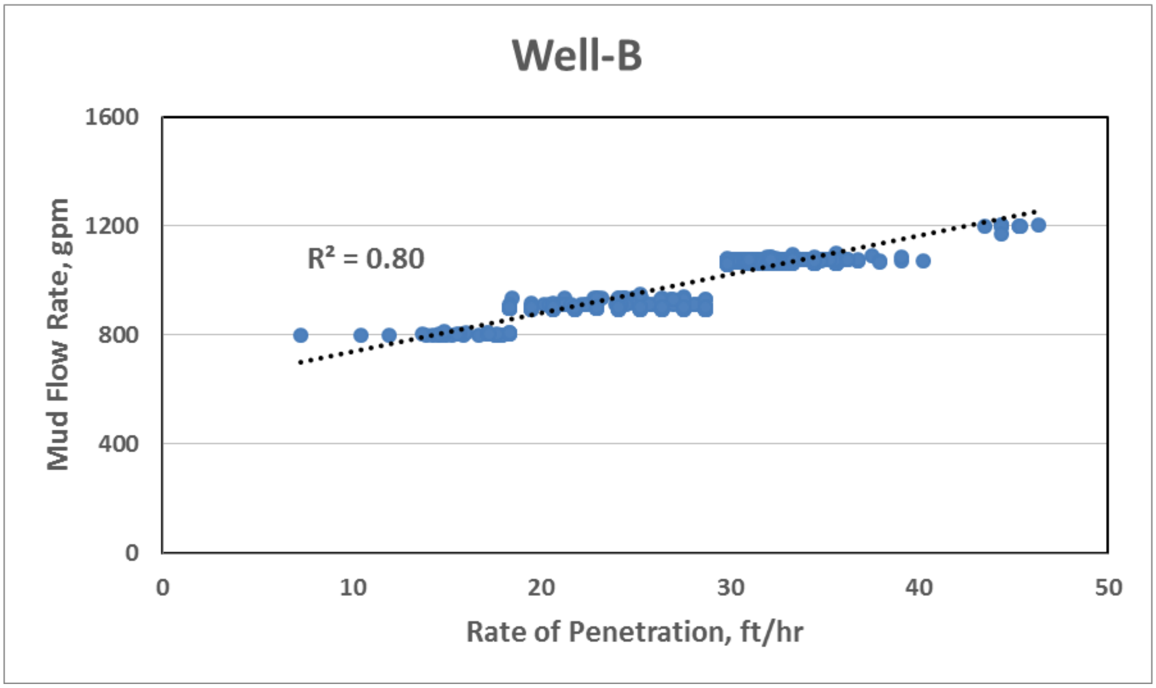

Figure 38: GPM vs. ROP for Well-B

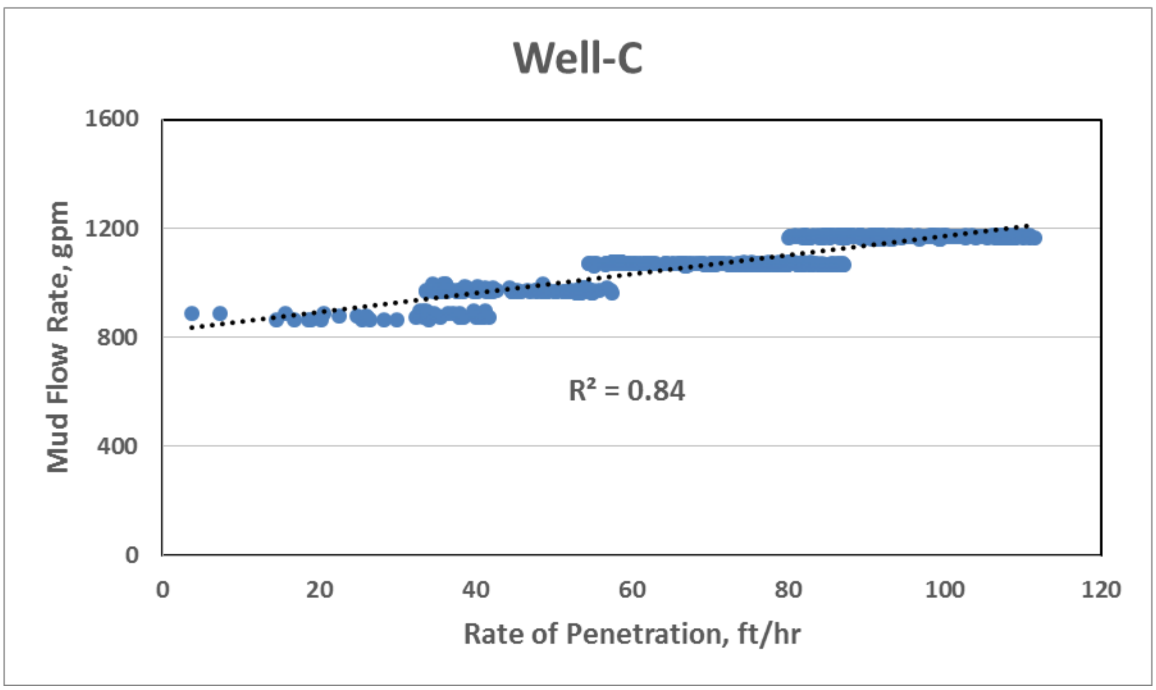

Figure 39: GPM vs. ROP for Well-C

5.2.6 Hydraulic horse power per Square Inch (HSI)

The term Hydraulic horse power per Square Inch (HSI) actually combines both SPP and GPM to gauge and measure the energy applied by the bit, and the unit for is Horse Power (HP). This parameter truly represents the combined hydraulic work done by the pumping rate and standpipe pressure, and the equation for is shown in equation 3.1 in Chapter 3. It is recommended always to keep 65% of the stand pipe pressure allocated for the pressure drop across the bit. When hydraulic horse power is plotted against the rate of penetration for all three wells as shown in Figures 40-42 it became clear that the relation is purely liner and there is a strong relationship between them. The average correlation coefficient R is 91% which suggest a very strong relationship, and the coefficient of determination R^2 is 82% on average implying that hydraulic horse power should be a strong part of the rate of penetration model.

The results displayed in the below three graphs clearly indicates a linear increase between rate of penetration and hydraulic horse power. This is clearly shows below since the term HSI already captures both parameters SPP and GPM. Well-C has already achieved higher horse power values and that what help it to achieve higher penetration rates. The reason these plots have data clusters away from each other is the stair or step plot type shown in the GPM charts. In the rate of penetration model, the term HSI will be accounted for since it gives better representation for GPM and SPP.

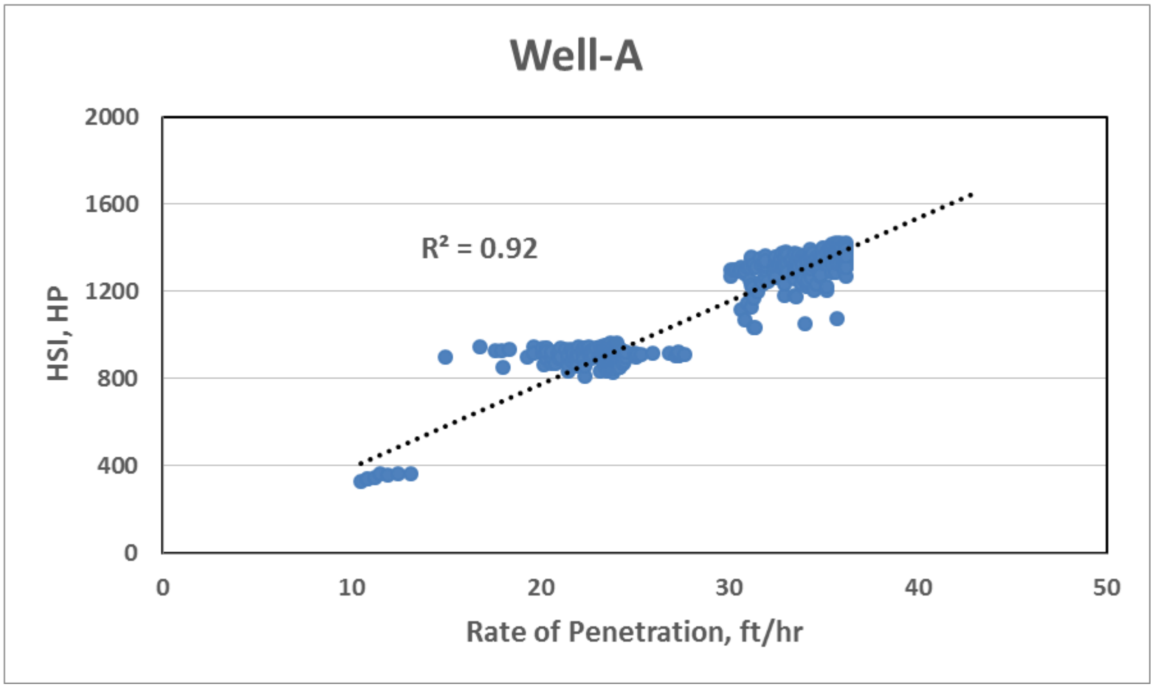

Figure 40: HSI vs. ROP for Well-A

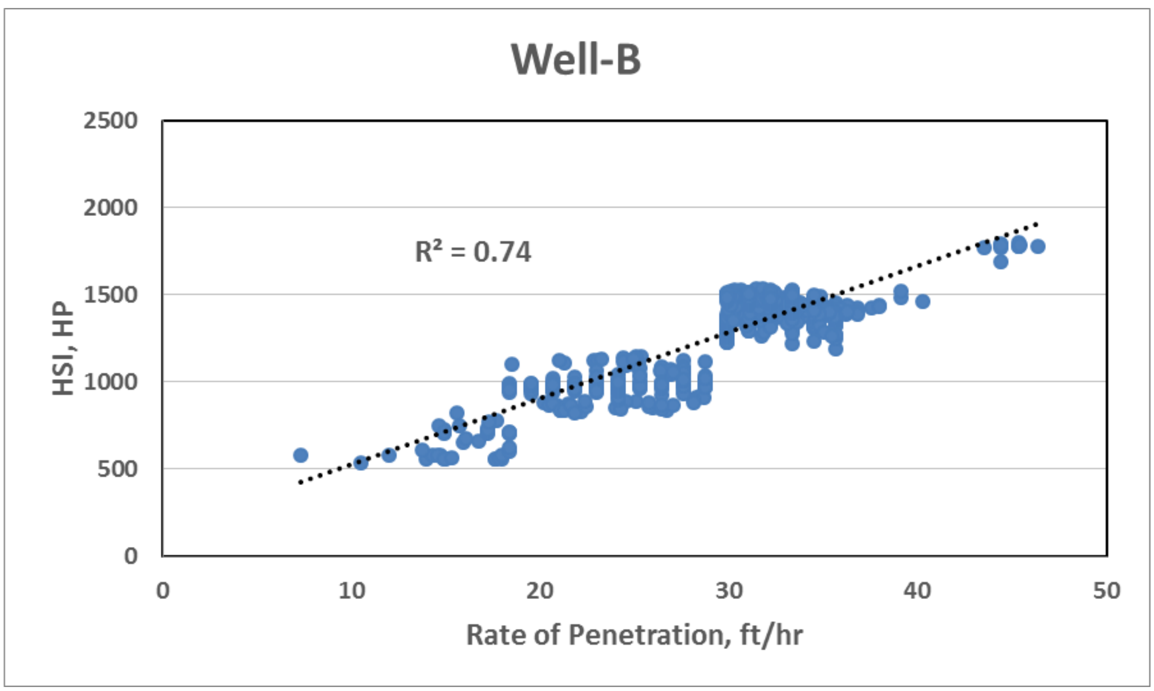

Figure 41: HSI vs. ROP for Well-B

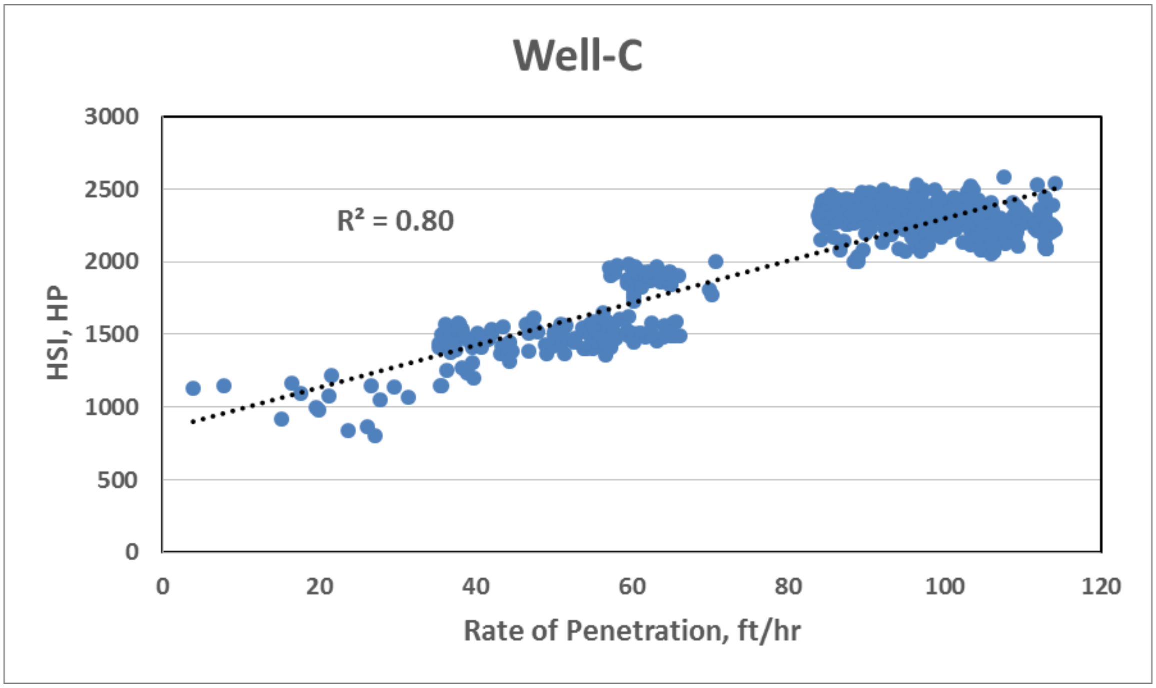

Figure 42: HSI vs. ROP for Well-C

5.3 Mud Properties Effect on ROP

After capturing the mud properties data of the entire field, they ware plotted against the rate of penetration. Two things will be captures here which are relation type and the coefficient of determination (R^2). Microsoft Excel will be used to plot the data and find the relation type and R^2 between the data set. All the results will be presented in the below sections. To better assurance in the results, an adjacent field was also used just to make sure that the results are conclusive.

5.3.1 Density (ρ)

The term density quantifies the heaviness of any fluid, which is very important parameter in drilling operation since it provided the necessary force to balance the formation pressure, and the unit for it is Pound per Cubic Foot (PCF). It also helps stabilize the formation and increase the wellbore stability. Even though this parameter is considered uncontrollable yet it impacts the rate of penetration in which it drops the ROP as it values increases. It has been known in the industry that rate of penetration increase during losses and kicks or when water is used as a drilling fluid, which hints how mud density impacts the drilling speed or progress.

When density is plotted against the rate of penetration for two adjacent fields as shown in Figures 43-44 it became clear that the relation is purely liner and there is a good relationship between them. The average correlation coefficient R is 84% which suggest a strong relationship, and the coefficient of determination R^2 is 71% on average implying that density can be a strong part of the rate of penetration model.

When looking the both graphs, it can be seen clearly that the data cluster on the left closer to water density, 64 pcf, scored the highest penetration rate, while the cluster on the right toward higher densities scored the lowest penetration rate values. This is known for the 'chip hold-down effect' where the heavy mud column strengthen the rock beneath it making it harder to cut and delays the releasing of the cuttings, as well as causing the drilling bit to bite the rock harder and restricting its movement.

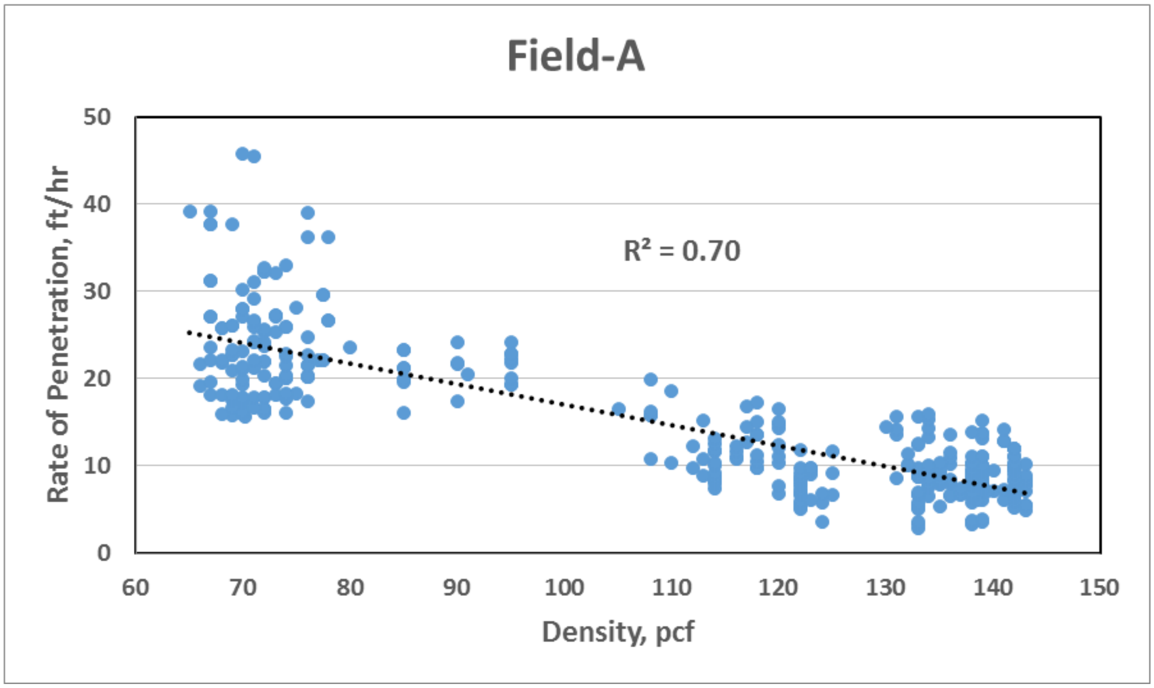

Figure 43: Density vs. ROP for Field-A

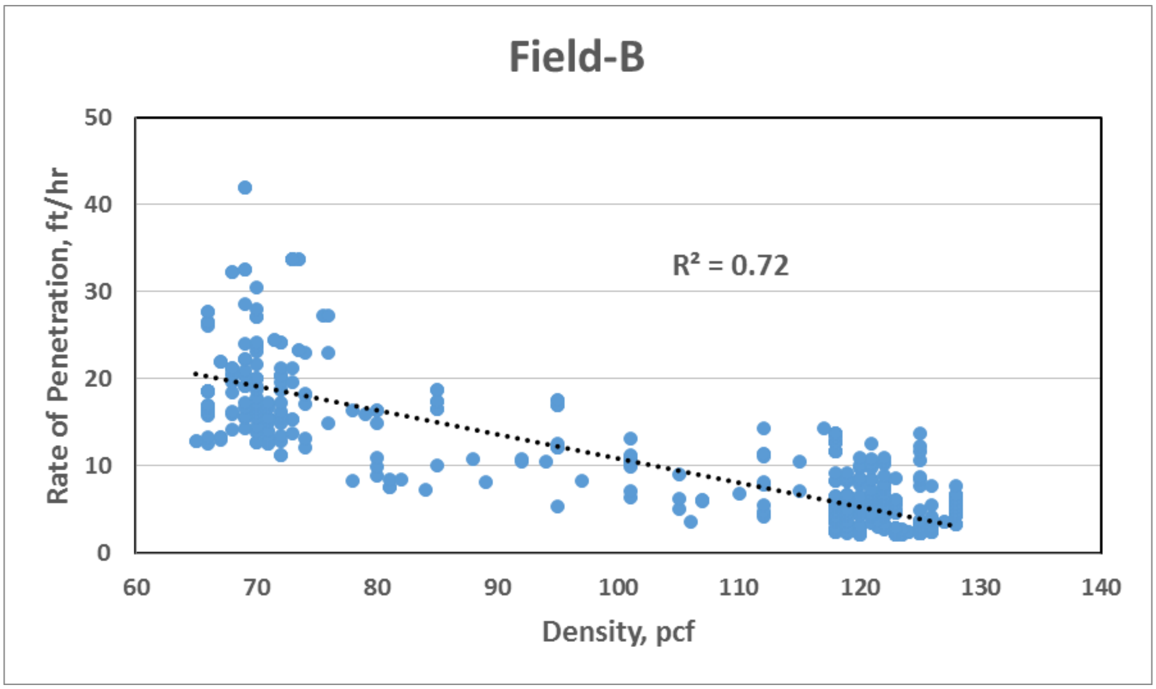

Figure 44: Density vs. ROP for Field-B

5.3.2 Funnel Viscosity (μ)

Funnel viscosity measures the resistance of fluid to flow due to shear force resistance between the particles, and the unit for it is 1/sec. It's used to reflect the carrying of the drilling mud and the developed gel strength once the mud becomes static. When funnel viscosity is plotted against the rate of penetration for two adjacent fields as shown in Figures 45-46 it became clear that no relationship exist between them.

When surveying through the literature, it was seen that most authors refers to the plastic viscosity when studying the viscosity effect on rate of penetration, not the funnel viscosity. Therefore, it is not a surprise to see that no direct relation exit between the funnel viscosity and the rate of penetration.

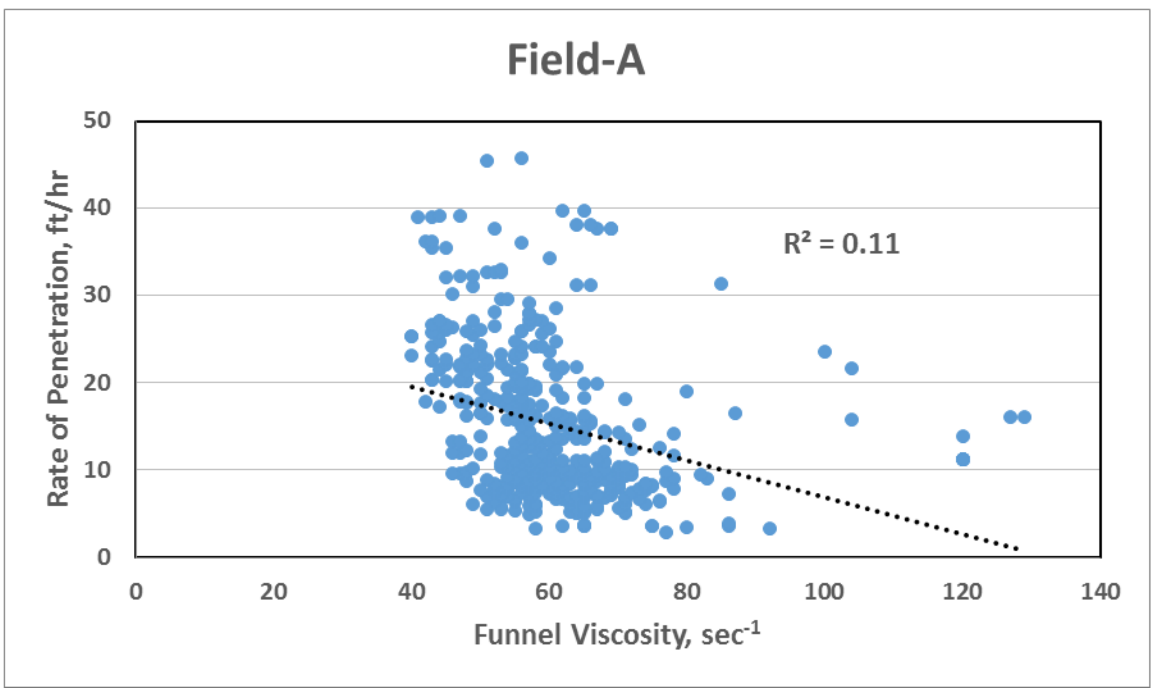

Figure 45: Funnel Viscosity vs. ROP for Field-A

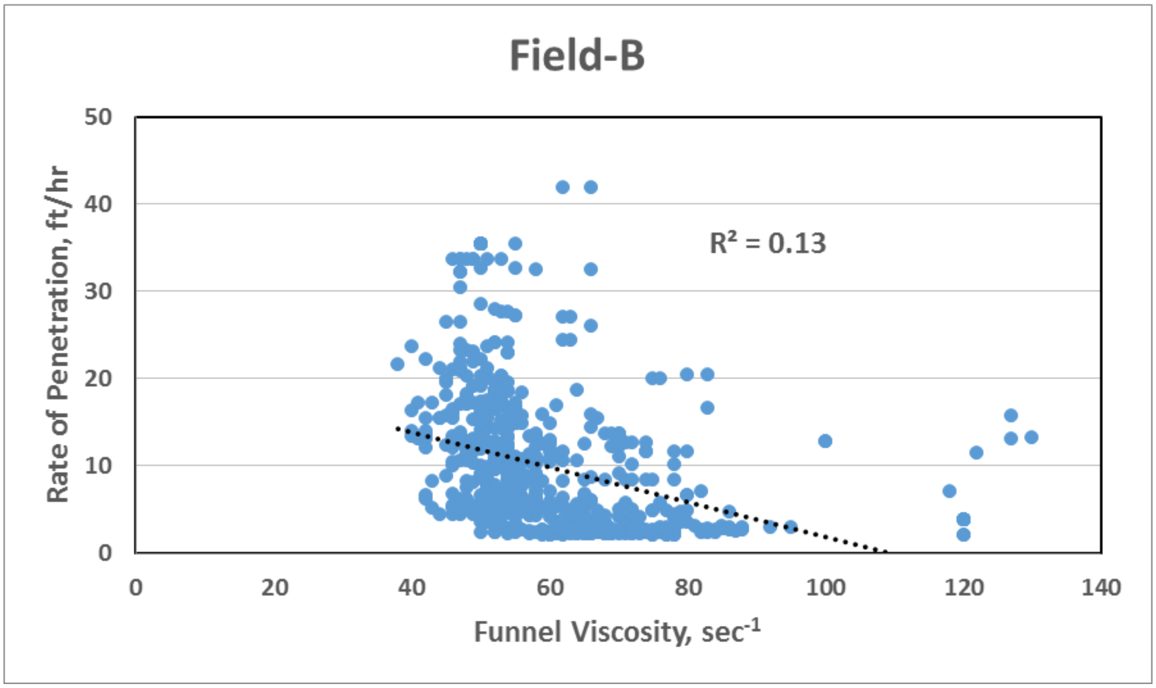

Figure 46: Funnel Viscosity vs. ROP for Field-B

5.3.3 Yield Point (YP)

Yield point reflects the initial force needed to move the mud due to the positive and negative attraction forces between the mud solids, and the unit for is lb/ft^2. In drilling terminology, it indicates the mud lifting ability of the drilled cuttings. As shown in equation 3.2 in Chapter 3 it is highly related to the plastic viscosity. When yield point is plotted against the rate of penetration for two adjacent fields as shown in Figures 47-48 it became clear that no relationship exist between them. Even though that yield point will enhance the hole cleaning yet other authors suggested that no significant impact between it and the rate of penetration occurs.

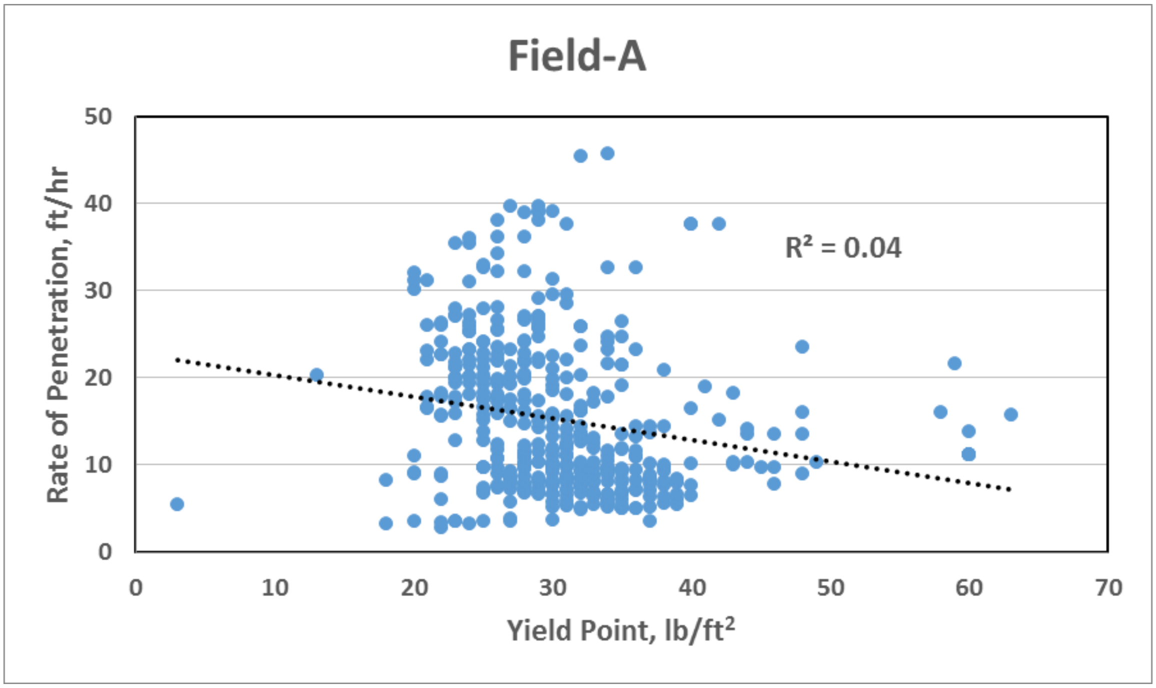

Figure 47: YP vs. ROP for Field-A

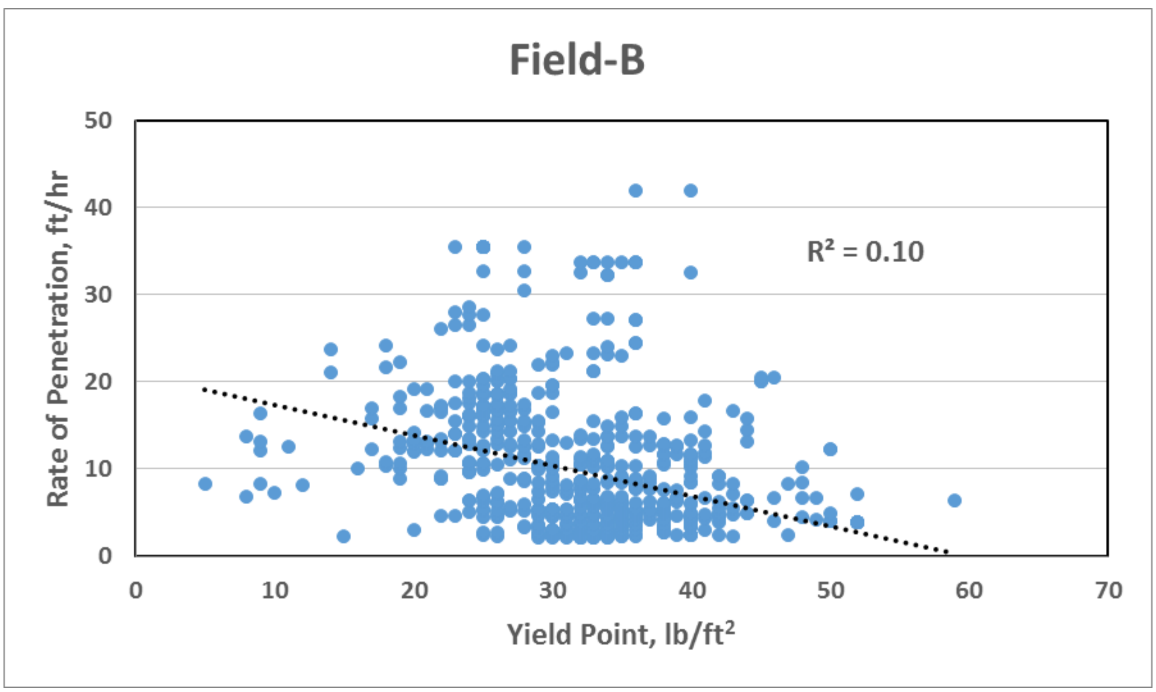

Figure 48: YP vs. ROP for Field-B

5.3.4 Plastic Viscosity (PV)

Even though this term involves viscosity in its naming, however it slight measures a different fluid behavior. The term plastic viscosity reflects the amounts of solids in the mud system, thus the true definition for it is: the resistance of the fluid movement due to shear force resistance between the particles or solids in the mud system, and it is reported in Centipoise (CP). This parameter often reflects the hole cleaning of the well, and the efficiency of the mud cleaning system.

When plastic viscosity is plotted against the rate of penetration for two adjacent fields as shown in Figures 49-50 it became clear that the relation is not liner (exponential) and there is a good relationship between them. The average correlation coefficient R is 82% which suggest a strong relationship, and the coefficient of determination R^2 is 68% on average implying that plastic viscosity can be a part of the rate of penetration model.

It can be concluded from the two graphs below that plastic viscosity varies non-linearly with the rate of penetration. Actually, the relation is more of an exponential which agrees with what previous authors suggested. Higher plastic viscosity values results in a thicker mud which reduces the bit and string motion when rotating. Also, it indicates the poorness of the hole cleaning which implies that some of the new rock cuttings are actually being cut and drilled again.

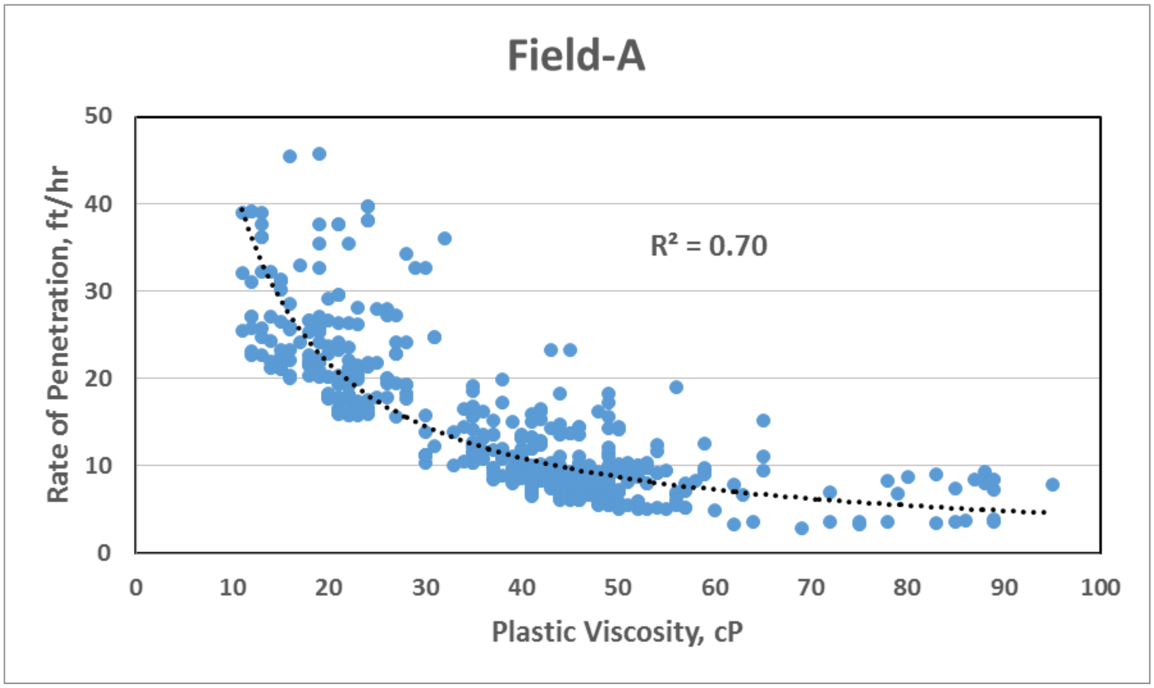

Figure 49: PV vs. ROP for Field-A

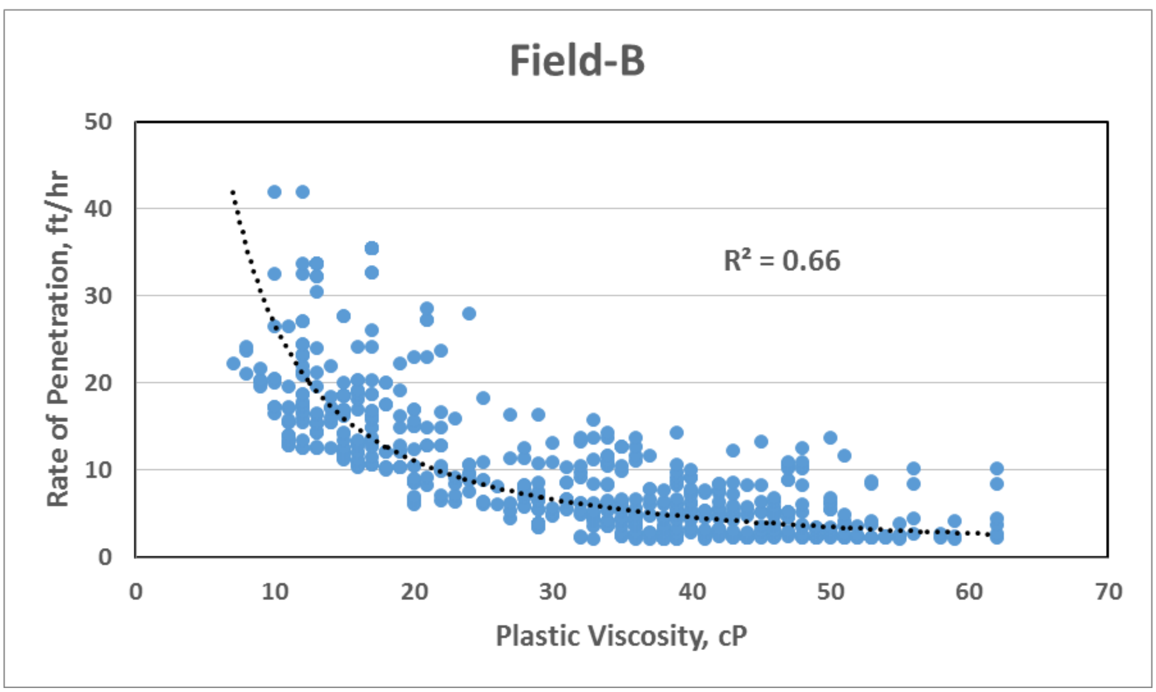

Figure 50: PV vs. ROP for Field-B

5.3.5 Solid Content (% Solids)

Solid content is highly related to plastic viscosity since it gives the percent of the solids in the system. Also, it increase with mud density increase since high mud density values relay in general on solid content such as the use of hematite or densities above 15 ppg or 110 pcf. It can cause serious washout and erosion to the drilling equipment downhole and on the surface if not controlled properly. Moreover, excessive solids can result in a high frictional force between the drilling string and the wellbore causing the torque to go higher, and as a result the RPM has to be reduced to avoid any equipment damage such as drill pipe twist-off.

When solid content is plotted against the rate of penetration for two adjacent fields as shown in Figures 51-52 it became clear that the relation is purely liner and there is a good relationship between them. The average correlation coefficient R is 83% which suggest a strong relationship, and the coefficient of determination R^2 is 69% on average implying that solid content can be a part of the rate of penetration model.

Even though there is a strong relation between solid content and plastic viscosity, yet the relation here is seen liner which agrees with some previous authors. When looking the both graphs, it can be seen clearly that the data cluster on the left closer to 10% solids scored the highest penetration rate which normally associated with lighter mud fluids, while the cluster on the right toward scored the lowest penetration rate values since it's more associated with higher mud densities that requires high solid amounts to reach it.

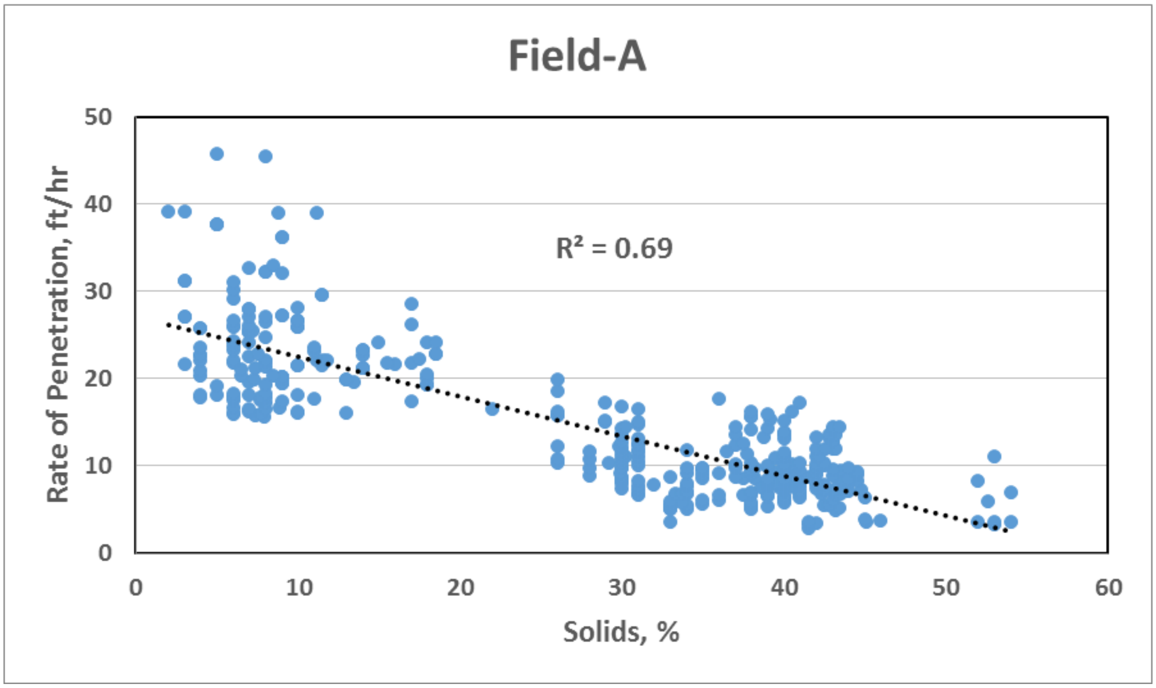

Figure 51: %Solids vs. ROP for Field-A

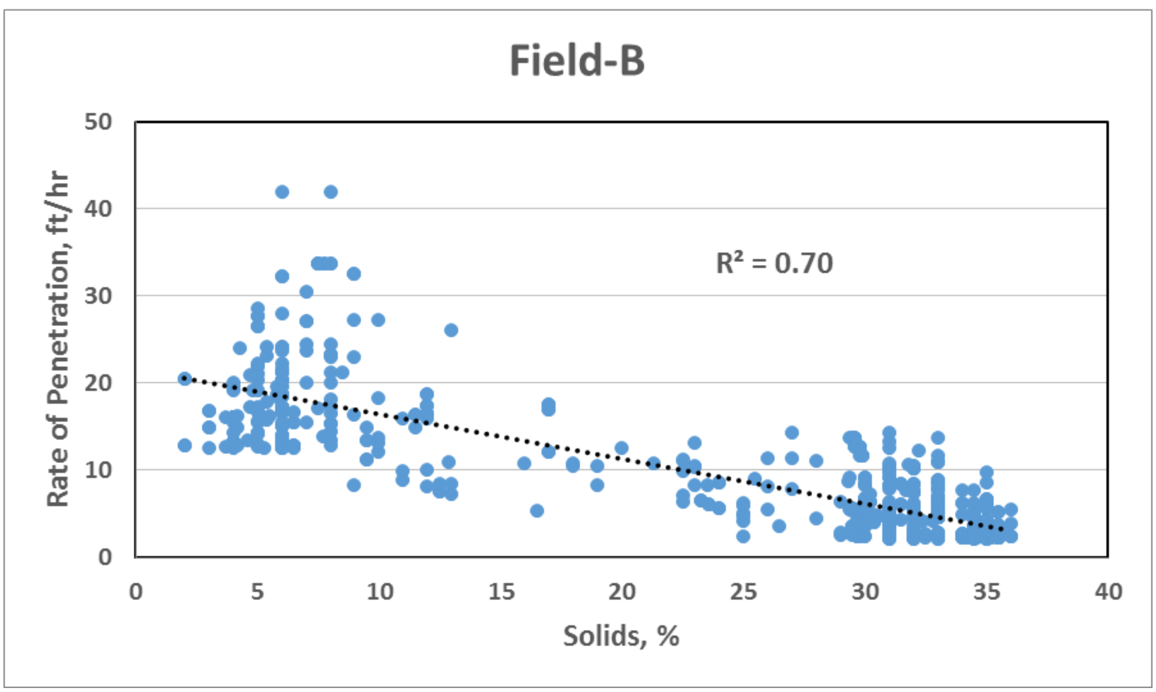

Figure 52: %Solids vs. ROP for Field-B

5.4 Rate of Penetration Model

After observing the mechanical, hydraulic and mud effects on rate of penetration, it is the time to develop a new ROP model that accounts for both mechanical parameters and mud properties. As stated before, the relationship type in phase II will be captured here in developing the model; those relations are summarized in Table 5. Also, a programming language was used to aid in some calculation especially some exponents. The ROP model will be developed on well-A then it will be tested on the two other wells, well-B and well-C. The beauty about the other two wells, especially well-C, is the high rate of penetration it scored and it is expected for the model to match its data closely.

Once the model is developed and tested on the other two wells, it will also be compared with some other models represented in the literature. Since most authors, if not all, didn't supply enough data with their models, the huge data presented in this work will be utilized. This will give a feeling of how accurate or precise the model is, and one can see the major differences between them whether it was the different parameters used or the model approach itself.

Figure 53: Model building and validation steps

Table 5: Comparison of different parameters effect on ROP with this research

<table>
<tr><th>Parameter</th><th>Author</th><th>Effect on ROP</th><th>This Research</th></tr>
<tr><td rowspan="8">RPM</td><td>Maurer</td><td>Linear</td><td rowspan="8">Linear</td></tr>
<tr><td>Galle and Woods</td><td>Exponential</td></tr>
<tr><td>Bingham</td><td>Linear</td></tr>
<tr><td>Bourgoyne and Young</td><td>Nonlinear (RPM^{a6})</td></tr>
<tr><td>Warren</td><td>Nonlinear (RPM^{b})</td></tr>
<tr><td>Teale</td><td>Linear</td></tr>
<tr><td>Pessier and Fear</td><td>Linear</td></tr>
<tr><td>Hareland</td><td>Nonlinear</td></tr>
<tr><td rowspan="8">WOB</td><td>Maurer</td><td>Square (WOB^2)</td><td rowspan="8">Nonlinear (WOB^{a})</td></tr>
<tr><td>Galle and Woods</td><td>Nonlinear (WOB^{k})</td></tr>
<tr><td>Bingham</td><td>Nonlinear (WOB^{a5})</td></tr>
<tr><td>Bourgoyne and Young</td><td>Nonlinear (WOB^{a5})</td></tr>
<tr><td>Warren</td><td>Square (WOB^{2})</td></tr>
<tr><td>Teale</td><td>Linear</td></tr>
<tr><td>Pessier and Fear</td><td>Linear</td></tr>
<tr><td>Hareland</td><td>Nonlinear</td></tr>
<tr><td rowspan="2">Solid Content</td><td>Eckel</td><td>No relation</td><td rowspan="2">Inverse Relation (Linear)</td></tr>
<tr><td>Paiaman</td><td>Inverse Relation (Linear)</td></tr>
<tr><td rowspan="4">Plastic Viscosity</td><td>Eckel</td><td>Inverse Relation (Exponential)</td><td rowspan="4">Inverse Relation (Exponential)</td></tr>
<tr><td>Beck</td><td>Inverse Relation (Exponential)</td></tr>
<tr><td>Paiaman</td><td>Inverse Relation (Linear)</td></tr>
<tr><td>Alum</td><td>Inverse Relation (Exponential)</td></tr>
<tr><td rowspan="2">Mud Density</td><td>Eckel</td><td>Inverse Relation (Field Observation)</td><td rowspan="2">Inverse Relation (Linear)</td></tr>
<tr><td>Paiaman</td><td>Inverse Relation (Linear)</td></tr>
</table>

5.4.1 Building the Model

From the previous section it was captured how different mechanical parameters and properties interact differently with rate of penetration. Table 6 below summarizes them and hints the ROP model setup. Bit area and formation compressive strength have been added to the proposed model since they are too essential and basic properties for any ROP model.

Table 6: Summary of all parameters and properties affecting ROP

Parameter	Effect on ROP	Curve Behavior
WOB	Direct	Straight Line
RPM	Direct	Straight Line
Torque	Direct	Straight Line
SPP	Direct	Straight Line
GPM	Direct	Straight Line
HSI	Direct	Straight Line
Mud Density	Inverse	Straight Line
Funnel Viscosity	No direct effect observed	No relation
YP	No direct effect observed	No relation
PV	Inverse	Exponential
Solid Content	Inverse	Straight Line

This implies the following mathematical relations:

$$\boldsymbol{ROP \propto WOB} \tag{5.1}$$

$$\boldsymbol{ROP \propto RPM} \tag{5.2}$$

$$\boldsymbol{ROP \propto Torque} \tag{5.3}$$

$$\boldsymbol{ROP \propto SPP} \tag{5.4}$$

$$\boldsymbol{ROP \propto GPM} \tag{5.5}$$

$$\boldsymbol{ROP \propto \frac{1}{\rho}} \tag{5.6}$$

$$\boldsymbol{ROP \propto \frac{1}{PV}} \tag{5.7}$$

$$\boldsymbol{ROP \propto \frac{1}{\%Solids}} \tag{5.8}$$

$$\boldsymbol{ROP \propto \frac{1}{Bit\ diameter}} \tag{5.9}$$

$$\boldsymbol{ROP \propto \frac{1}{UCS}} \tag{5.10}$$

As stated before, HSI will replace GPM and SPP, but for better model representation it can be kept. Moreover, PV and %Solids are highly related thus only PV will be accounted for in the model.

Summarizing all the above equation yields to:

$$\boldsymbol{ROP} \propto \frac{\boldsymbol{WOB}\times\boldsymbol{RPM}\times\boldsymbol{T}\times\boldsymbol{SPP}\times\boldsymbol{GPM}}{\boldsymbol{d_b^2}\times\boldsymbol{\rho}\times\boldsymbol{PV}\times\boldsymbol{UCS}} \tag{5.11}$$

Even though the results mostly show a linear relation, yet it is better to check all exponents for any parameter. This was suggested by many authors and in fact most of them ended up developing their own exponents. There will a total of seven exponents as shown below:

$$\boldsymbol{ROP} \propto \frac{\boldsymbol{WOB^a}\times\boldsymbol{RPM^b}\times\boldsymbol{T^c}\times\boldsymbol{SPP^d}\times\boldsymbol{GPM^e}}{\boldsymbol{d_b^2}\times\boldsymbol{\rho^f}\times\boldsymbol{PV^g}\times\boldsymbol{UCS^h}} \tag{5.12}$$

To perform this, non-linear regression is needed where all parameters will be calculated using different exponent until the right exponent is found. The most convenient method was using a plug-in for Excel called XLSTAT which is a statistical tool cable of performing many statistics including non-linear regression. To gauge the effect of each individual parameter, one parameter at a time will be assigned to observe the maximum capability of that individual parameter.

5.4.2 Determining the Model Coefficients

Once Excel is loaded, XLSTAT add-on can be open at the last tab as shown in Figure 54, then the Modeling-data drop list can be opened and Nonlinear Regression can be chosen.

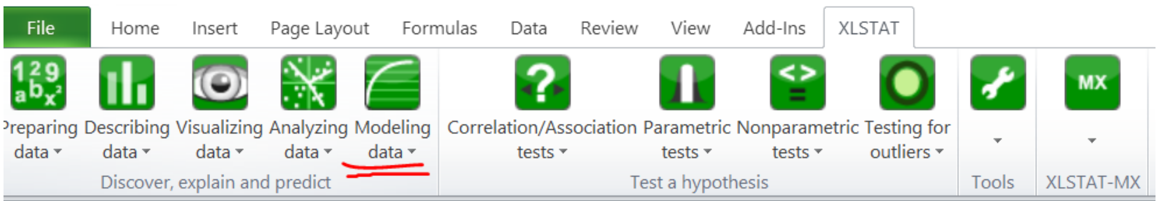

Figure 54: XLSTAT interface

From the right pane on Figure 55, two inputs are required. The first one, labeled 1 or Y, required the LHS input which ROP column. The second label, or X, requires the other inputs columns which are the rest of all parameters.

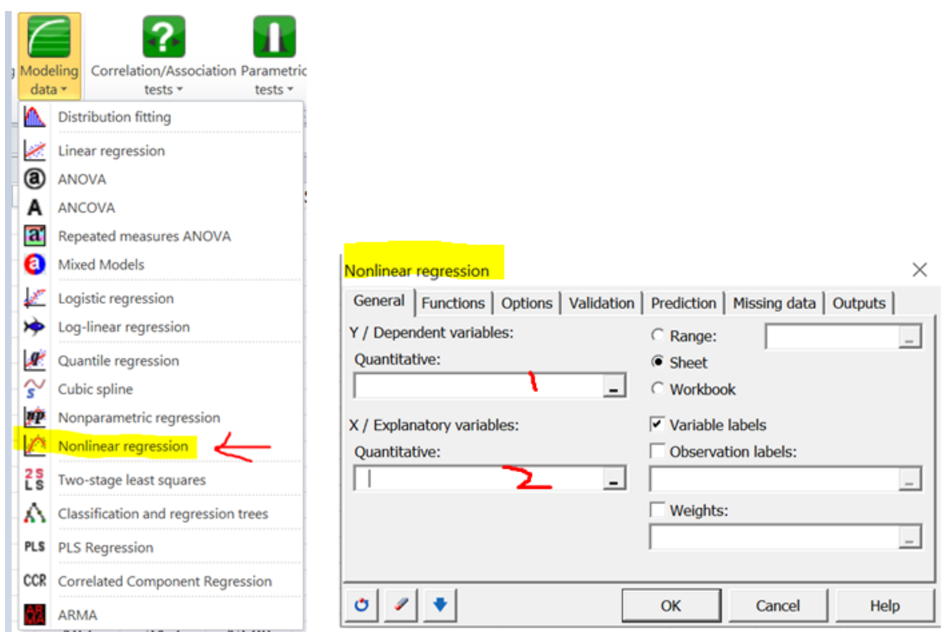

Figure 55: XLSTAT nonlinear regression

The next tab, functions, shown in Figure 56 asks for the type of equation to be calculated. For example, if the effect of the GPM exponent was to be calculated then GPM will be assigned to X1 and its exponent will be pr1, while the rest of parameters will not have any exponent. This will continue until all exponents are found.

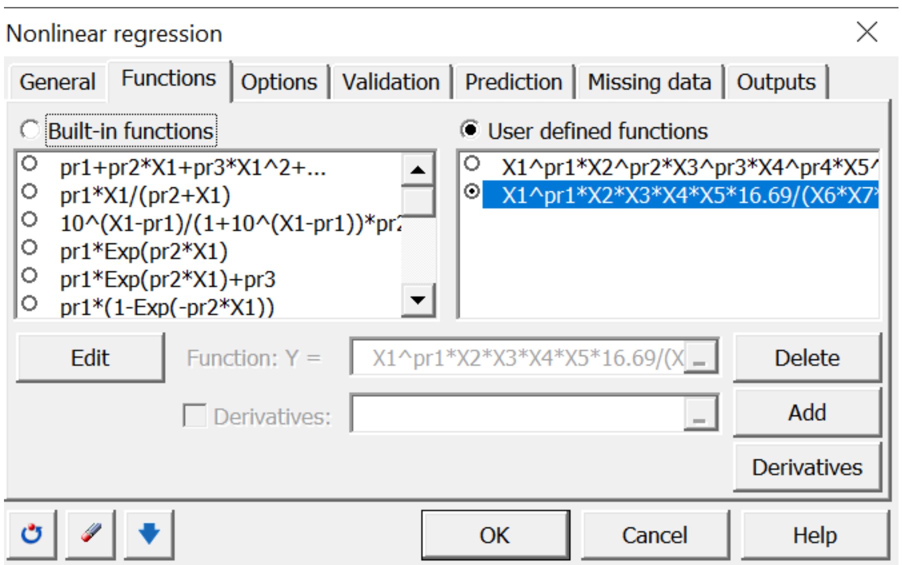

Figure 56: Defining XLSTAT functions

After performing this step, the software will perform nonlinear regression to estimate the best exponent that results in the best fit. Off course no best fit will occur, however, it will be known if that parameter affects the rate of penetration linearly or with higher or lower exponent. Figure 57 shows a summary for XLSTAT on the GPM output with an exponent close to one.

XLSTAT 2014.5.03 - Nonlinear regression - on 10/1/2016 at 3:26:57 PM
Y / Quantitative: Workbook = Correlation.xlsx / Sheet = Well-A / Range = 'Well-A'!$B:$B / 1072 rows and 1 column
X / Quantitative: Workbook = Correlation.xlsx / Sheet = Well-A / Range = 'Well-A'!$C:$J / 1072 rows and 8 columns
Stop conditions: Iterations = 200 / Convergence = 0.00001
Function: Y = X1^pr1*X2*X3*X4*X5*16.69/(X6*X7*X8*16^2)
Seed (random numbers): 1334228261

Summary statistics:

Variable	Observations	vith missin	thout missi	Minimum	Maximum	Mean	:d. deviation
ROP, ft/hr	1072	0	1072	22.590	42.270	35.371	4.036
GPM X_1	1072	0	1072	889.000	970.000	907.506	4.428
RPM	1072	0	1072	159.000	188.000	173.277	9.379
WOB, Klbf	1072	0	1072	15.000	40.900	28.733	5.457
Torque, Kl	1072	0	1072	7.980	18.950	12.992	1.839
SPP, psi	1072	0	1072	1934.000	2799.000	2584.979	110.589
Density, P(	1072	0	1072	73.000	78.000	75.392	0.841
PV	1072	0	1072	20.000	26.000	22.463	2.572
UCS, psi	1072	0	1072	21000.000	40000.000	29613.806	7180.877

Correlation matrix:

Variables	GPM	RPM	WOB, Klbf	orque, Klbf-	SPP, psi	Density, PCF	PV	UCS, psi	ROP, ft/hr
GPM	**1.000**	0.147	-0.014	-0.114	0.077	-0.121	0.018	0.065	-0.081
RPM	0.147	**1.000**	-0.185	-0.319	-0.565	-0.521	-0.209	-0.248	-0.062
WOB, Klbf	-0.014	-0.185	**1.000**	0.449	0.086	-0.324	-0.682	-0.612	-0.015
Torque, Kl	-0.114	-0.319	0.449	**1.000**	-0.011	-0.066	-0.489	-0.467	0.414
SPP, psi	0.077	-0.565	0.086	-0.011	**1.000**	0.484	0.381	0.439	0.000
Density, P(	-0.121	-0.521	-0.324	-0.066	0.484	**1.000**	0.647	0.638	0.001
PV	0.018	-0.209	-0.682	-0.489	0.381	0.647	**1.000**	0.987	-0.087
UCS, psi	0.065	-0.248	-0.612	-0.467	0.439	0.638	0.987	**1.000**	-0.100
ROP, ft/hr	-0.081	-0.062	-0.015	0.414	0.000	0.001	-0.087	-0.100	**1.000**

Nonlinear regression of variable ROP, ft/hr:

Goodness of fit statistics:

Observati(	1072.000
DF	1071.000
R²	0.023
SSE	274449.203
MSE	256.255
RMSE	16.008
Iterations	2.000

Model parameters:

Parameter	Value
pr1	0.942

Equation of the model:

ROP, ft/hr = GPM^0.941592925697396*RPM*WOB, Klbf*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi*16^2)

Figure 57: Example of XLSTAT output summary

This method carries on until all exponents are found. It should be mentioned that exponents less or more than one by 15% should be counted as purely linear. On the other hand, exponents that are more that 15% should not be considered as linear and that exponent need to be calculated.

Model parameters:

Parameter	Value
pr1	0.982

Equation of the model:

ROP, ft/hr = GPM*RPM^0.982355188672974*WOB, Klbf*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi*16^2)

Model parameters:

Parameter	Value
pr1	0.396

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf^0.396417798641409*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi*16^2)

Model parameters:

Parameter	Value
pr1	0.940

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf*Torque, Klbf-ft^0.940247174483071*SPP, psi*16.69/(Density, PCF*PV*UCS, psi*16^2)

Model parameters:

Parameter	Value
pr1	0.932

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf*Torque, Klbf-ft*SPP, psi^0.932411831483158*16.69/(Density, PCF*PV*UCS, psi*16^2)

Figure 58a: Summary of exponents calculated by XLSTAT 1

Model parameters:

Parameter	Value
pr1	1.047

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF^1.04666572248072*PV*UCS, psi*16^2)

Model parameters:

Parameter	Value
pr1	1.100

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV^1.10015757928154*UCS, psi*16^2)

Model parameters:

Parameter	Value
pr1	1.609

Equation of the model:

ROP, ft/hr = GPM*RPM*WOB, Klbf*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi^1.60881568497376*16^2)

Figure 59: Summary of exponents calculated by XLSTAT 2

It can be seen from Figures 58 that only WOB and UCS vary non-linearly with the rate of penetration. Even though PV was shown to vary non-linearly with rate of penetration, yet it was shown by XLSTAT calculation that a linear relation for it should be fine. I believe the reason for that is limited data available for PV against the rate of penetration. As stated before, if this 16" section took only 2 days to drill, then there will only four data points for the plastic viscosity, each at 12 hours separation.

The table below summarizes all exponent calculated by XLSTAT.

Table 7: Summary of exponents calculated by XLSTAT

Parameter	Effect on ROP	XLSTAT Exponent
WOB	Direct	**0.396**
RPM	Direct	0.982
Torque	Direct	0.940
SPP	Direct	0.932
GPM	Direct	0.942
Mud Density	Inverse	1.046
PV	Inverse	1.100
UCS	Inverse	**1.608**

Now taking all the above exponents back into to equation 5.12 such that all of them are to the power one except WOB and UCS yields:

$$\boldsymbol{ROP \propto \frac{WOB^{a} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{b}}} \tag{5.13}$$

OR

$$\boldsymbol{ROP = \frac{WOB^{a} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{b}}} \tag{5.14}$$

Prior to finding the final model, all the units should be matching each other in field unit. Taking equation 5.14 and unifying all the units resulted in the below:

$$GPM = \frac{Gallons}{min} = 0.1336\ \frac{ft^3}{min} \tag{5.15}$$

$$SPP = UCS = psi = \frac{lb}{in^2} \tag{5.16}$$

$$HSI = \frac{SPP \times GPM}{1714} \tag{5.17}$$

$$RPM = \frac{rev}{min} = \frac{2\pi.rad}{min} \tag{5.18}$$

$$Torque = lb - ft = lb \times ft \tag{5.19}$$

$$\rho = pcf = \frac{lb}{ft^3} \tag{5.20}$$

$$PV = cp = 2.42\,\frac{lb}{ft \times hr} \tag{5.21}$$

Putting all units above in equation 5.14 yields:

$$ROP = \frac{\cancel{lb} \times \frac{2\pi.rad}{min} \times \cancel{lb} \times ft \times \frac{\cancel{lb}}{\cancel{in^2}} \times 0.1336\,\frac{ft^3}{min}}{1714 \times in^2 \times \frac{\cancel{lb}}{ft^3} \times 2.42 \frac{\cancel{lb}}{ft \times hr} \times \frac{\cancel{lb}}{\cancel{in^2}}} \tag{5.22}$$

$$ROP = \frac{\frac{60}{hr} \times ft \times 0.1336\,\frac{60 * ft^{\cancel{3}}}{\cancel{hr}}}{1714 \times \frac{ft^{\cancel{2}}}{144} \times \frac{2.42}{ft^4 \times \cancel{hr}}} \tag{5.23}$$

This leaves equation 5.23 with the following constants:

$$\boldsymbol{ROP = \frac{3600\times0.1336\times144}{1714\times2.42} = 16.96} \tag{5.24}$$

Thus, equation 5.14 becomes:

$$\boldsymbol{ROP = 16.96\times\frac{WOB^{a}\times RPM\times T\times SPP\times GPM}{d_b^2\times\rho\times PV\times UCS^{b}}} \tag{5.25}$$

The final step now is to calculate the two exponents ‘a’ and ‘b’. Using the same approach in the statistical software, the model will be undergoing a nonlinear regression calculations with both ‘a’ and ‘b’ constants unknown to determine the best value for them. The value of ‘a’ was found to be 0.85 and ‘b’ of 1.16, and Figure.59 shows the result. Looking at Figure.59, the data can be seen without a good fit and some shift occurs around the four different formation boundaries. Here, the idea of using data clustering came to place in which each formation should be treated differently during the non-linear regression. Since there are four formations that exist, four different values of ‘b’ are expected. On the other hand, only one bit exponent value for ‘a’ is expected which is specifically tied to the 16” seven bladed PDC bit used.

Figure 60 and Table 8 summarizes all the exponents found. The ‘a’ exponent corresponding for that specific bit used was 0.85, while the ‘b’ exponent corresponding to each formation was decreasing as the UCS increases.

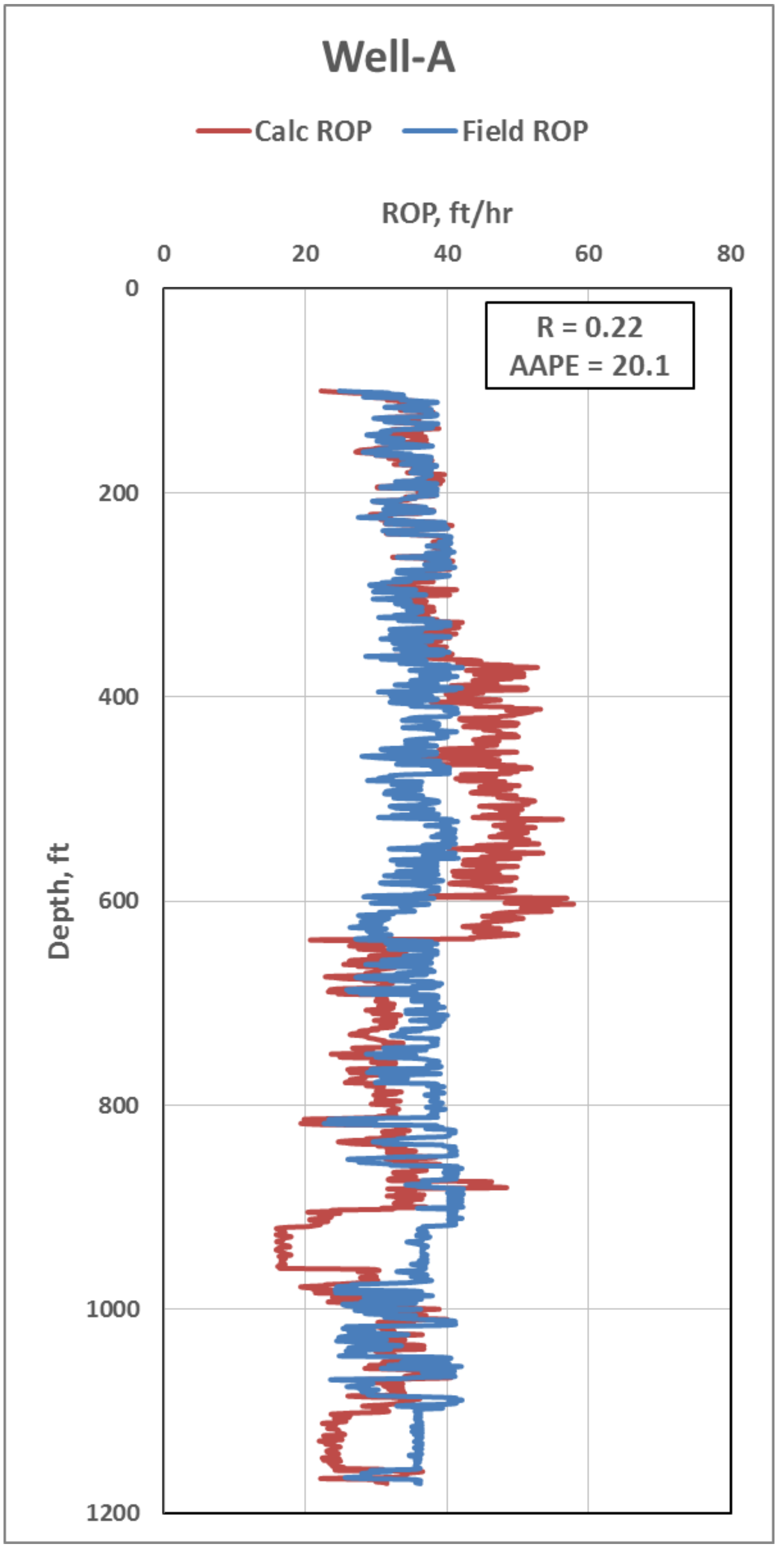

Figure 59: Calc ROP vs. Field ROP for Well-A before data clustering

Model parameters:

Parameter	Value
pr1	0.849
pr2	1.169

Equation of the model:

Calc ROP = GPM*RPM*WOB, Klbf^0.848963671395167*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi^1.16922354234248*16^2)

Model parameters:

Parameter	Value
pr1	0.852
pr2	1.160

Equation of the model:

Calc ROP = GPM*RPM*WOB, Klbf^0.851852084262992*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi^1.15970986385554*16^2)

Model parameters:

Parameter	Value
pr1	0.850
pr2	1.084

Equation of the model:

Calc ROP = GPM*RPM*WOB, Klbf^0.85000000000026*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi^1.08395818741353*16^2)

Model parameters:

Parameter	Value
pr1	0.854
pr2	1.036

Equation of the model:

Calc ROP = GPM*RPM*WOB, Klbf^0.853517222568466*Torque, Klbf-ft*SPP, psi*16.69/(Density, PCF*PV*UCS, psi^1.03598562330477*16^2)

Figure 60: Summary of 'a and b' exponents calculated by XLSTAT

Table 8: Summary of 'a and b' exponents calculated by XLSTAT

Exponent	Formation-A	Formation-B	Formation-C	Formation-D
a (WOB)	0.85			
b (UCS)	1.169	1.160	1.084	1.036

This finally brings equation 5.25 to the below. UCS values are summarized in Table 9.

Formation-A:

$$\boldsymbol{ROP = 16.96 \times \frac{WOB^{0.85} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{1.169}}} \tag{5.26}$$

Formation-B:

$$\boldsymbol{ROP = 16.96 \times \frac{WOB^{0.85} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{1.160}}} \tag{5.27}$$

Formation-C:

$$\boldsymbol{ROP = 16.96 \times \frac{WOB^{0.85} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{1.084}}} \tag{5.28}$$

Formation-D:

$$\boldsymbol{ROP = 16.96 \times \frac{WOB^{0.85} \times RPM \times T \times SPP \times GPM}{d_b^2 \times \rho \times PV \times UCS^{1.036}}} \tag{5.29}$$

Table 9: Summary for UCS values for each formation

Parameter	**Formation-A**	**Formation-B**	**Formation-C**	**Formation-D**
UCS, psi	21,000	24,000	33,000	40,000
b	1.169	1.160	1.084	1.036

Figures 61 and 62 shows the comparison between field data and the model for well-A.

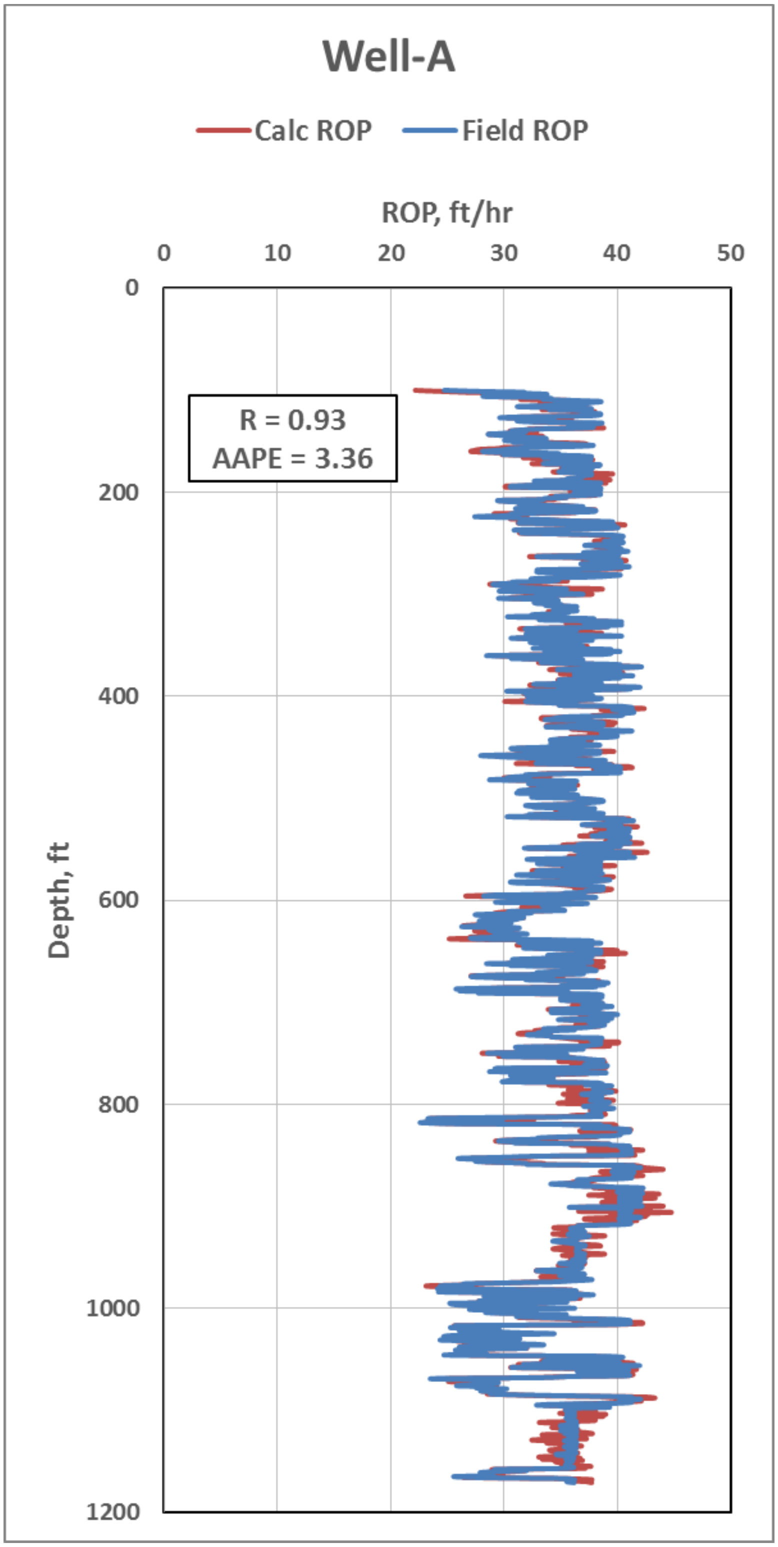

Figure 61: Calc ROP vs. Field ROP for Well-A after clustering

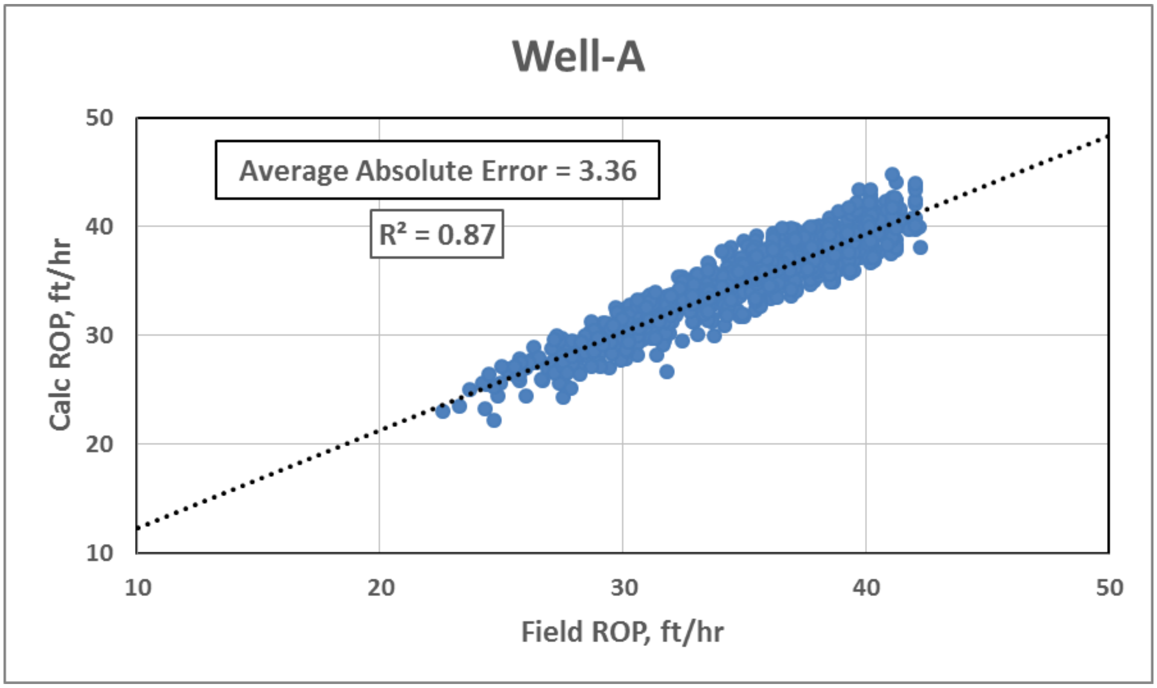

Figure 62: Correlation coefficient for Well-A

5.4.3 Validating and Testing the Model

After developing the model for each induvial formation and having a good value for the coefficient of determination (R^2) and correlations coefficient (R), it should be tested and validated using other well's data. As indicated previously, two other wells with the same section will be utilized to test the proposed model. Each formation was tested against its corresponding equation. The plots of the field and calculated ROP both well-B and well-C are displayed below in Figures 63-66.

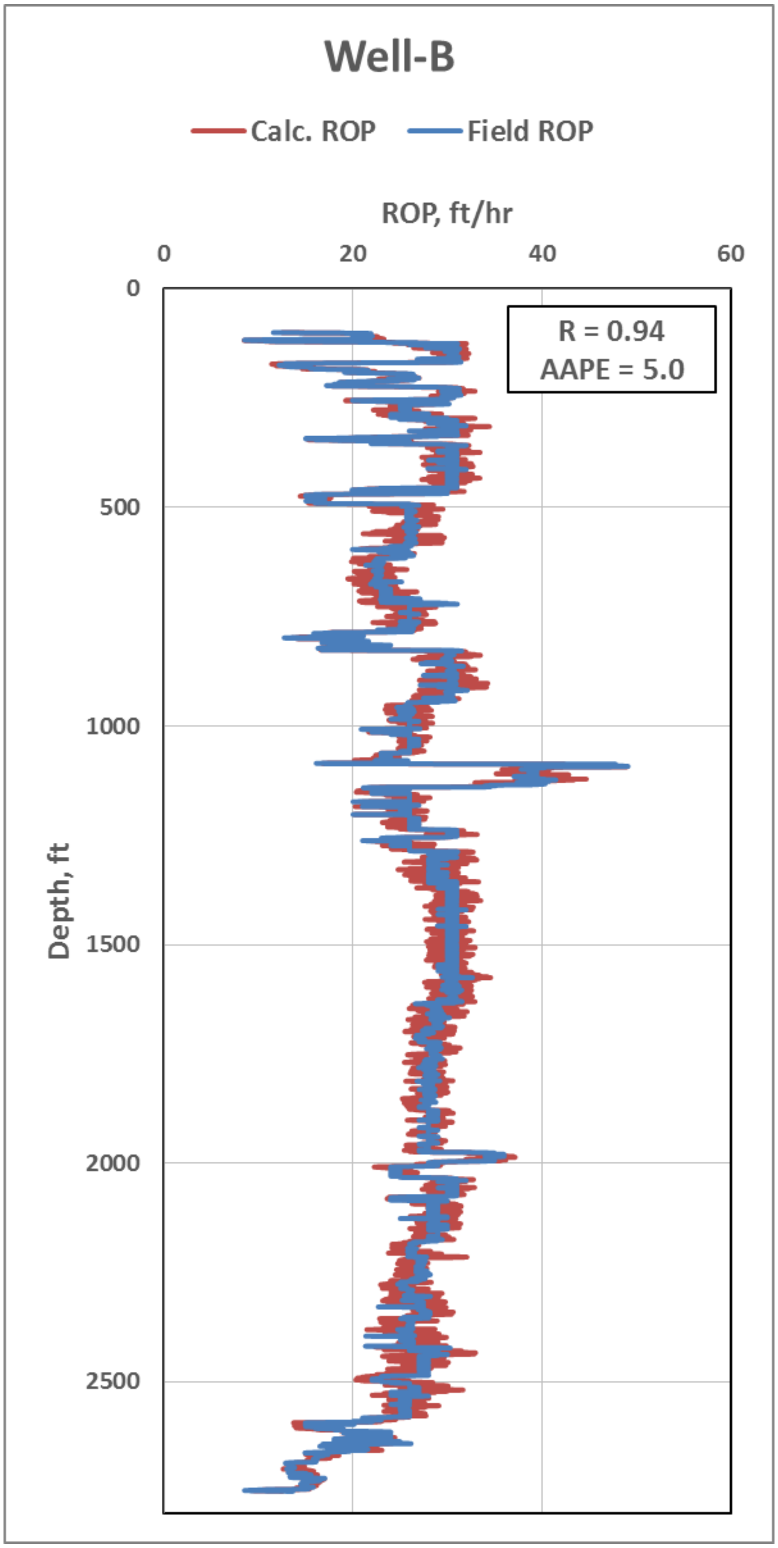

Figure 63: Calc ROP vs. Field ROP for Well-B

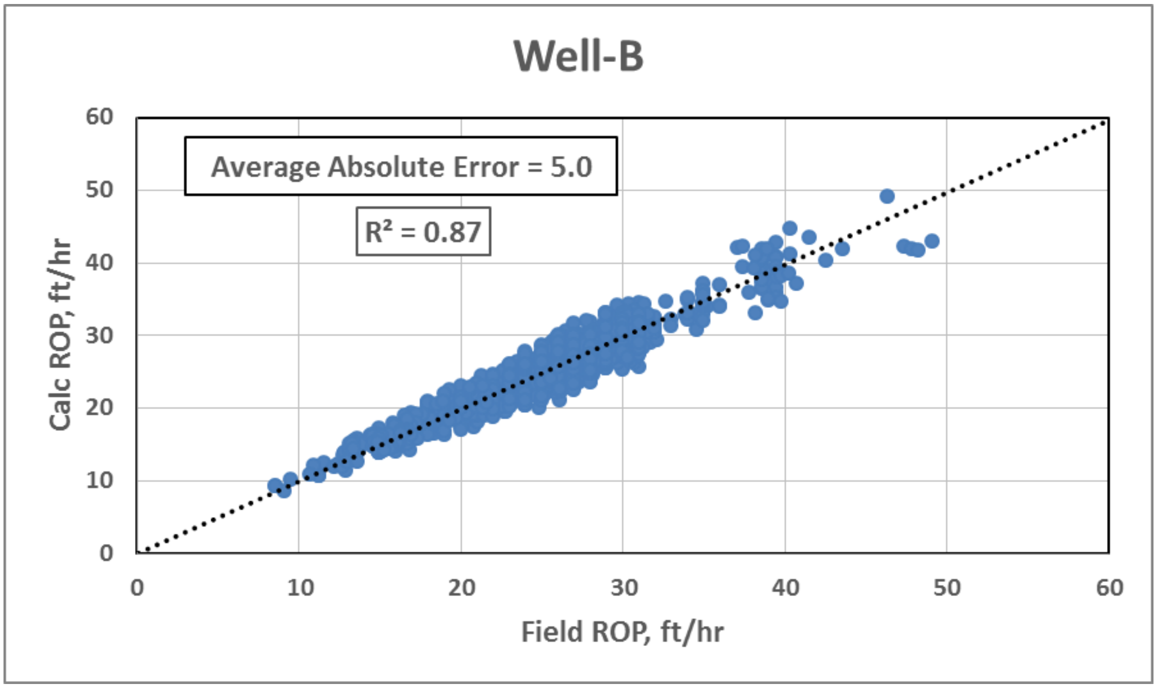

Figure 64: Correlation coefficient for Well-B

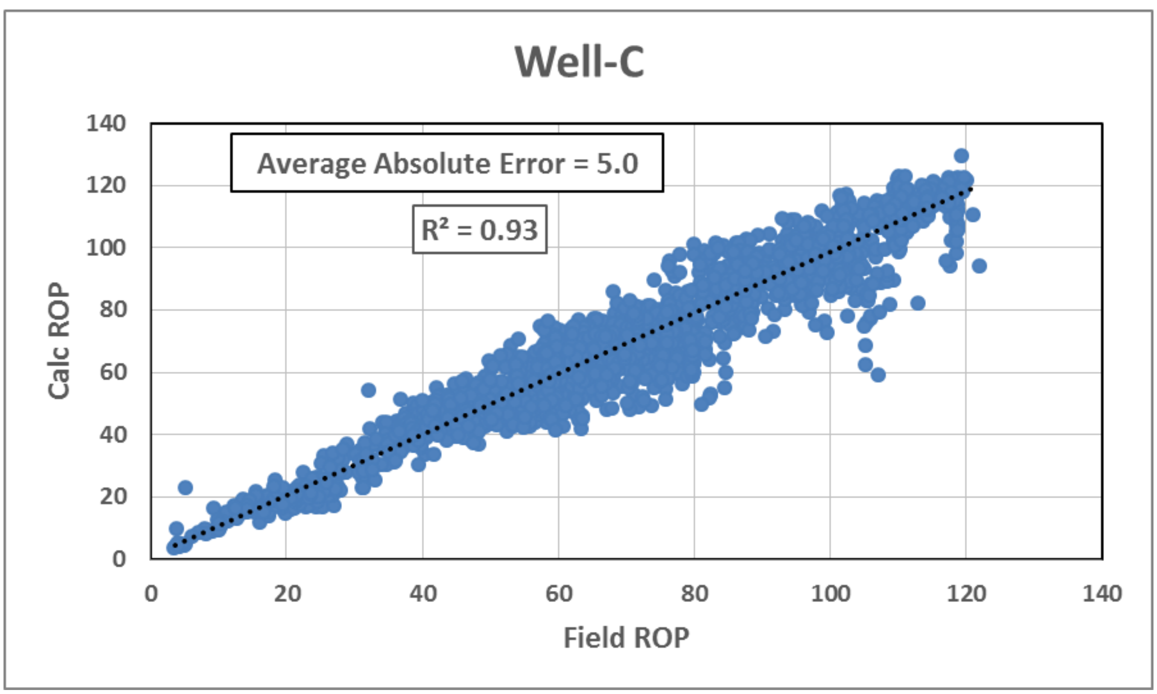

Figure 65: Correlation coefficient for Well-C

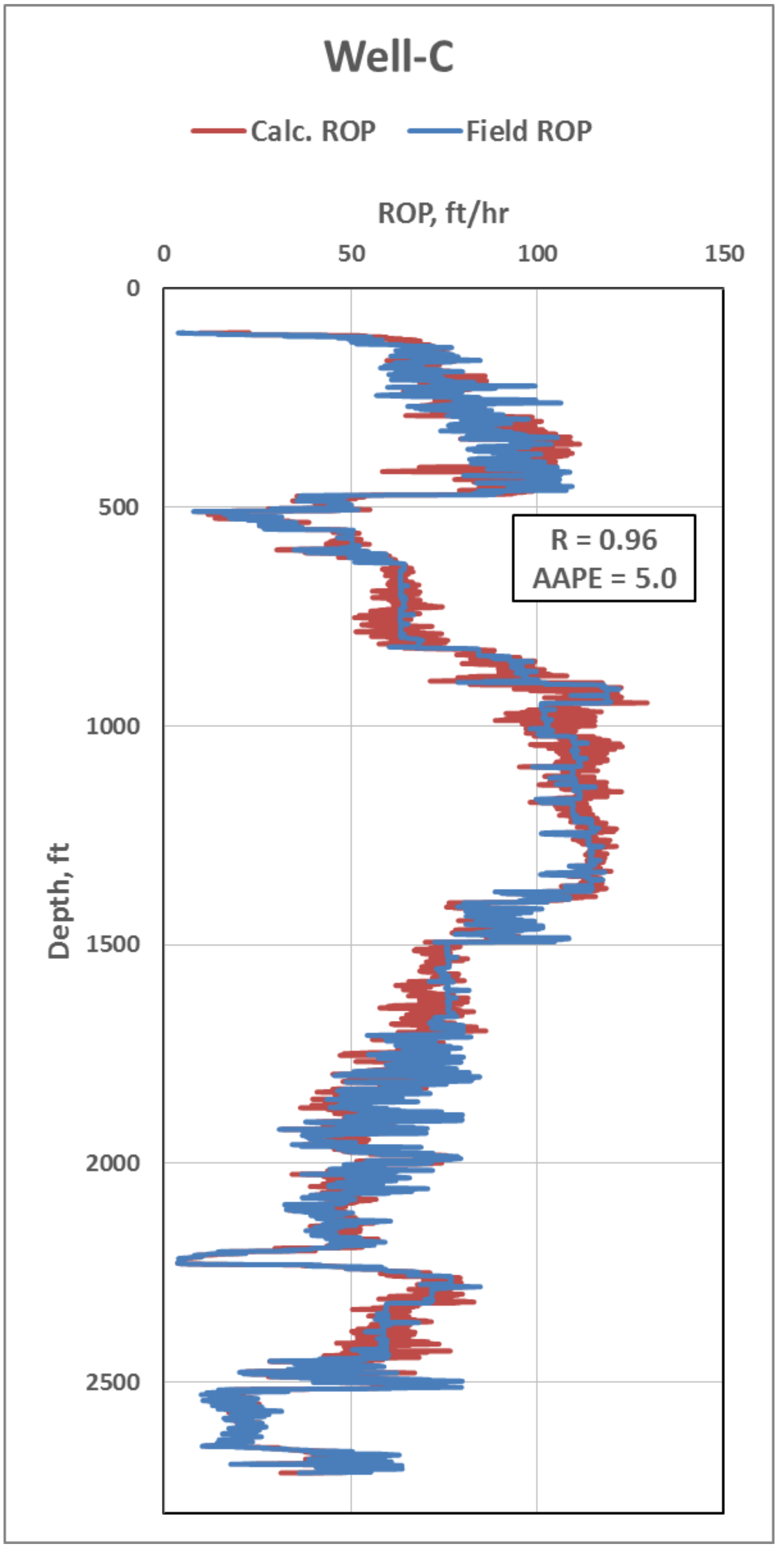

Figure 66: Calc ROP vs. Field ROP for Well-C

It can be seen that both wells showed excellent data fitting and resulted in very good R^2 value. Also, it can be noticed that the more data was provided the better the fitting was. This newly developed ROP model accounts for both mechanical parameters and mud properties. All of the relationship types in phase II were captured here in this the model. Even though well-C scored the highest rate of penetration yet the model was able to predict its values precisely. This was possible because drilling hydraulics, especially HSI, were captured in this model. All the ROP data spikes whether it was dropping or increasing were predicted by this model since most of them were a drop in some parameters such as WOB and RPM.

Table 10: Summary of R and R^2 for all wells

Parameter	Well-A	Well-B	Well-C
R	0.93	0.94	0.96
R^2	0.87	0.87	0.93
AAPE	3.36%	5%	5%

Using this developed model, future rate of penetration values can be predicted once the bit started drilling some footage across one formation. This will enable further optimizations for all parameters and ensure achieving the best possible values for the rate of penetration. It should be mentioned that the exponent ‘a’ is tied to a single bit type and that has been proved using the three wells data. On the other hand the exponent ‘b’ varies from one well or location to another since all these formations are heterogeneous and formation properties changes from one place to another.

This even might enable the mapping off all ‘b’ exponent values, then using kriging method to predict any other needed values in any nearby well. The approach introduced in this research can be used to develop the same model for different fields, or even different hole size section.

5.4.4 Comparison with Other Models

After developing the model and testing it on two different wells, it is time to compare it with other models represented in the literature. Since most authors, if not all, didn’t supply enough data with their models, the huge data presented in this work will be utilized. This will give a feeling of how accurate or precise the model is, and one can see the major differences between them whether it was the different parameters used or the model approach itself.

To be fair in picking the other models, recent and old correlations will be used including the most famous ones. This will even show the major differences between them and how one model differ from the other. Since there are mainly two types of models in the industry, both of them will be considered which are conventional ROP models and Mechanical Specific Energy (MSE) ROP models. For the MSE model, Teale and Armenta models will be used. For the ROP models, the famous Bourgoyne & Young model will be used in addition to Bingham and Maurer. This makes them a total of five models which should be enough in the comparison.

The five models to be selected are shown below with all necessary steps needed to perform the calculation and the outputs.

Maurer (1962):

$$\boldsymbol{R = k\frac{NW^2}{{d_b}^2 UCS^2}} \tag{5.30}$$

d_b = bit diameter, in	k = drillability constant	N = rotary speed, RPM
W = weight on bit, lbs	UCS = strength of rock, psi	R = drilling rate, ft/hr

The approach here is to perform a regression to calculate the constant k, then use the equation to generate the plot. Using XLSTAT, k was found to be equal to 29434783.7 then it was plug back in the equation to calculate the value of the rate of penetration. As shown in Figure 67, the results are around the actual ROP in the first two formations, however, the rate of penetration for Maurer model dropped significantly after that. I believe this is due to having the unconfined compressive strength to the power of two which makes the model poor in handling high values of it across deeper sections. Also note that torque, hydraulics and mud properties are not captured in this model.

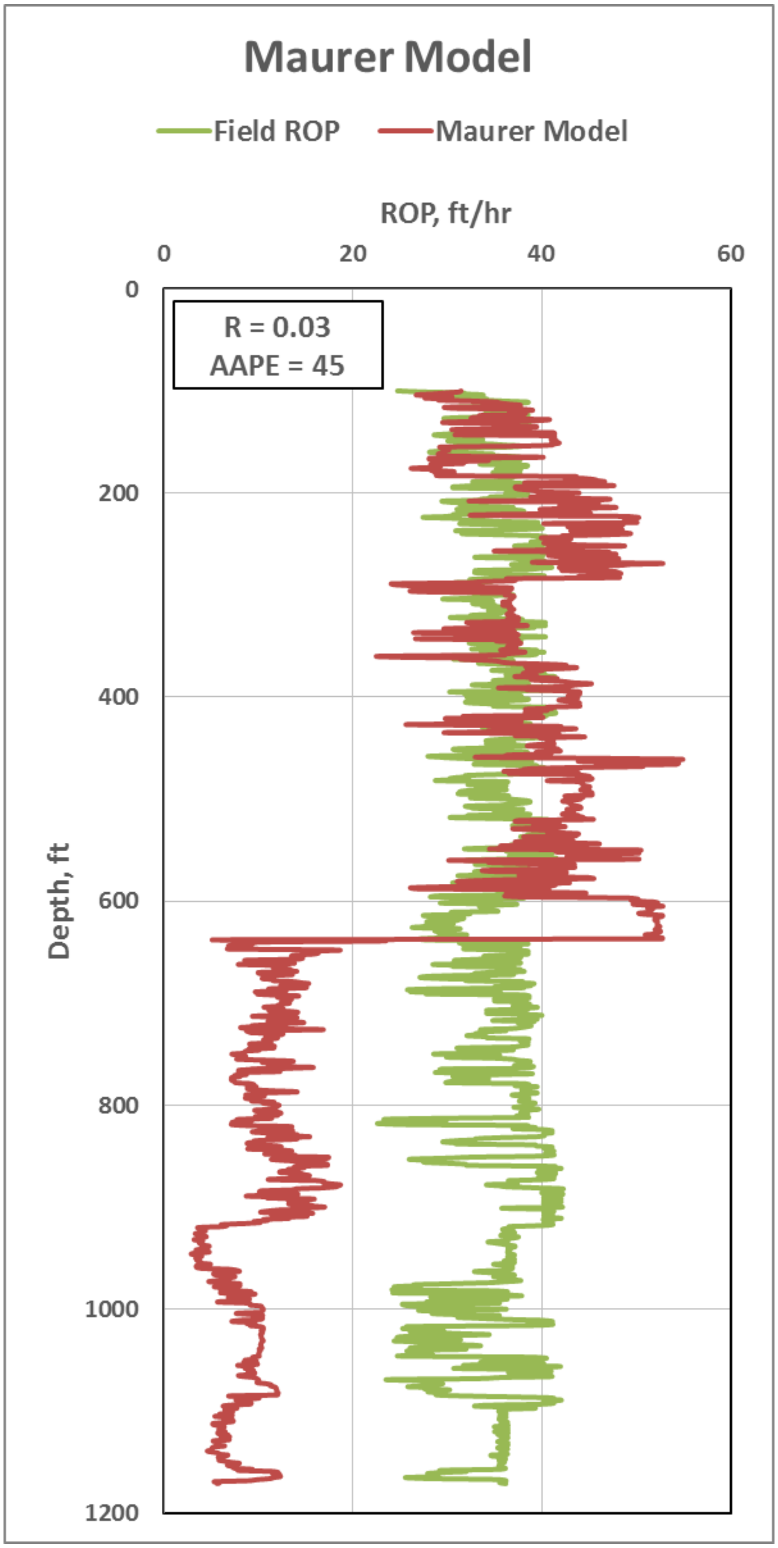

Figure 67: Comparison with Maurer ROP model

Bingham (1965):

$$\boldsymbol{R = K\left(\frac{W}{d_b}\right)^{a} N^{b}} \quad (5.31)$$

a = bit weight exponent b= RPM exponent K = drillability constant

Similar to what was done previously, all three exponents need to be calculated to define the final form of the equation. Using XLSTAT, K was found to be 3.025, 'a' was 0.020 and 'b' was 0.475. Plugging those exponents back to the equation to calculate the rate of penetration resulted in the plot shown in Figure 68 next page. The resulted ROP from Bingham model appears to be non-fluctuating and centered in the middle of the actual ROP. It is like smoothing the data and averaging it to nice narrow line hinting the direction of the values. This model doesn't allow the optimization of the ROP based on the parameters, instead it can give a feeling of the average ROP value. Note that torque, hydraulics, mud properties and formation strength are not also captured in this model.

Table 11: Bingham ROP model exponents

Exponent	Value
K	3.025
a (WOB)	0.020
b (RPM)	0.475

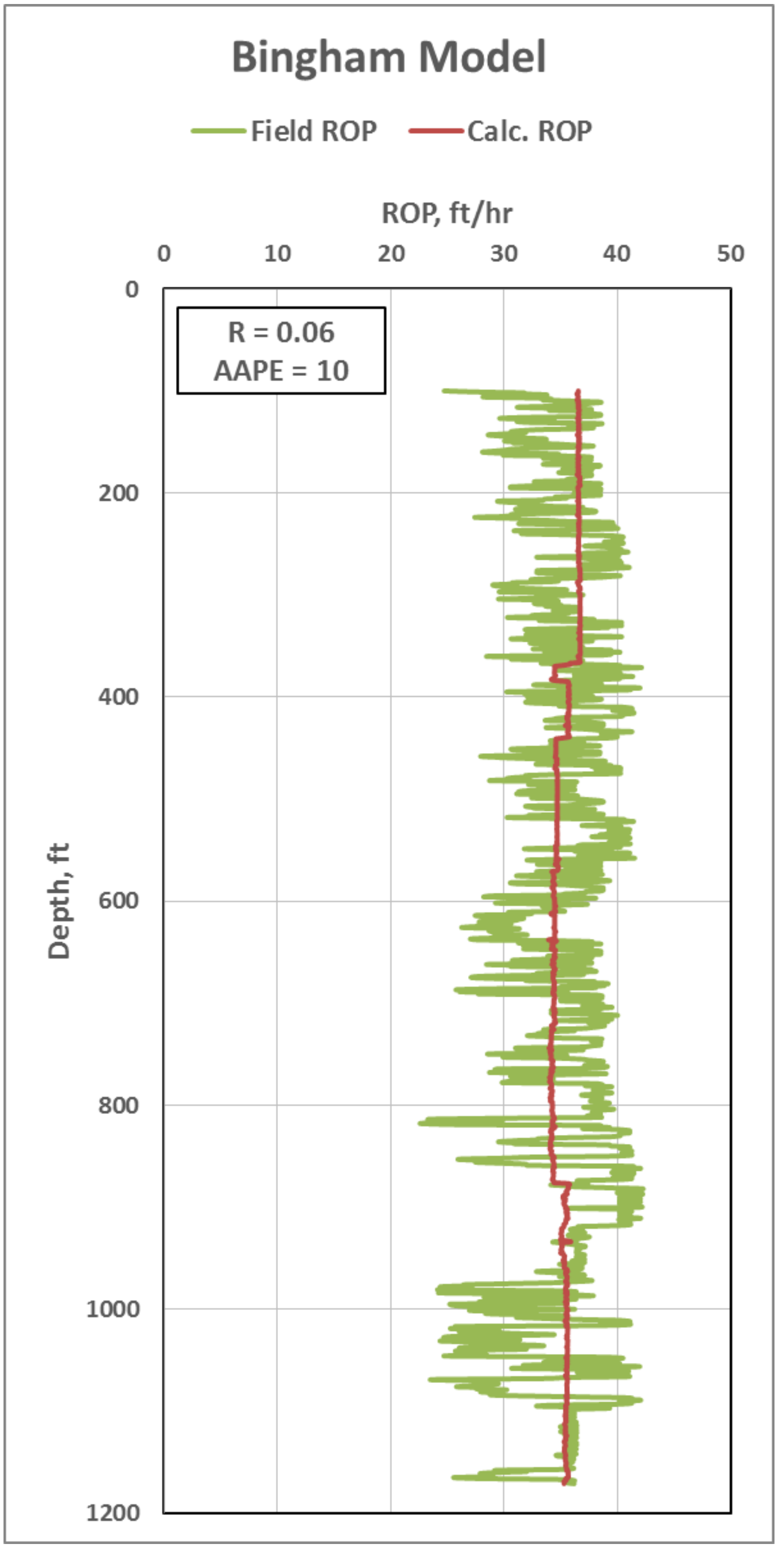

Figure 68: Comparison with Bingham ROP model

Bourgoyne and Young's (1973 and 1974):

$$\frac{d}{dt}(R) = e^{\left(a_1 + \sum_{i=2}^{8} a_i x_i\right)} \tag{5.32}$$

$$x_1 = 1.0 \qquad x_2 = 10,000 - TVD \qquad x_3 = TVD^{0.69}\left(g_p - 9.0\right)$$

$$x_4 = TVD\left(g_p - \rho_{ec}\right) \qquad x_5 = \ln\left\{\frac{\frac{WOB}{d_b} - \left(\frac{WOB}{d_b}\right)_t}{4.0 - \left(\frac{WOB}{d_b}\right)_t}\right\} \qquad x_6 = \ln\frac{N}{100}$$

$$x_7 = -h \qquad x_8 = \ln\left\{\frac{\rho_m}{350\mu d_n}\right\}$$

This model needs to be put in one single equation using the following assumptions:

- No WOB threshold yields to $x_5 = \ln\left\{\frac{WOB}{4d_b}\right\}$
- The PDC came out in good condition which eliminate using x_7 parameter
- The term g_p is the Equivalent Mud Weight (EMW) and equals to 64 pcf (8.56 ppg) in the first thee section, and 68 pcf (9.1 ppg) in the last section
- ρ_{ec} is the Equivalent Circulating Density (ECD) and equals to 2 pcf above current mud weight
- μ is the plastic viscosity
- d_n is the nozzle size and equals to 15/30 or 0.5 in.

Now adding all the above parameters under equation 5.32 yields to:

$$\boldsymbol{ROP} = e^{a_1} e^{a_2(10{,}000-TVD)} e^{a_3 TVD^{0.69}(EMW-67.39)} e^{a_4 TVD(EMW-ECD)} \left(\frac{WOB}{4d_b}\right)^{a_5} \left(\frac{N}{100}\right)^{a_6} \left(\frac{\rho_m}{350\mu d_n}\right)^{a_7}$$

The approach here is to perform a regression to calculate all 'a' constants, then use them into the equation to calculate the ROP and generate the plot. Using XLSTAT this multiple nonlinear regression was performed and the results are shown in Table 12 below. The small results for a_2-a_4 were not surprising since it almost makes the exponent value equals one which eliminate the effect of that parameter. Looking at the depth of the section and the overbalance exerted on the formation one can predict that it is negligible, and the same results were encounter by other authors such as Piaman[21]. Looking at Figure 69, the same behavior in Bingham model was encountered here even though Bingham model was easier to calculate.

Table 12: Bourgoyne & Young ROP model exponent

Exponent	Value
a_1	3.419882
a_2 (Compaction)	4.1E-05
a_3 (Overbalance)	-3.4E-05
a_4 (Differential)	1.21E-06
a_5 (Bit)	-0.04517
a_6 (RPM)	-0.31432
a_7 (Hydraulics)	0.072809

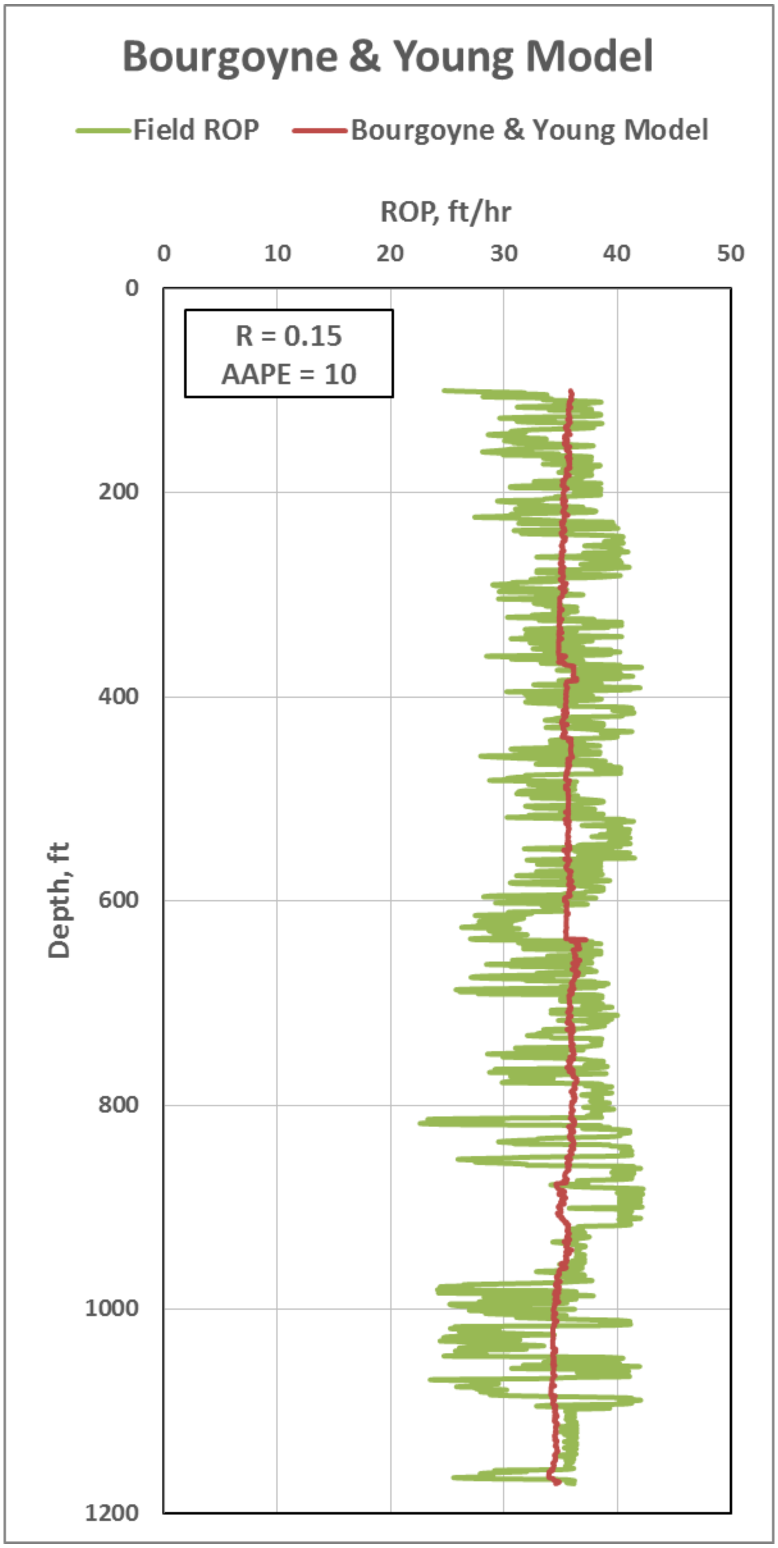

Figure 69: Comparison with Bourgoyne & Young ROP model

Teale (1965):

$$\boldsymbol{MSE = \left(\frac{480NT}{d_b^2 ROP}\right) + \left(\frac{4WOB}{\pi d_b^2}\right)} \quad (5.33)$$

d_b = Bit Diameter, in^2 T = Torque, lb-in

The Mechanical or Drilling Specific Energy (MSE or DSE) should equal to the rock's unconfined compressive strength for optimum drilling efficiency. Plugging the necessary data yielded to the plot in Figure 70 shown next page. Now the results should be equal to the UCS data presented in the section earlier, however, this was not the case. After some investigation, and surprisingly, Teale MSE model results was closer when compared with the parameter UCS^b, and b refers to the exponent calculated earlier for each formation. When UCS^b was plotted the results seemed more convenient, and somehow strengthened the approach of the ROP model proposed in this research.

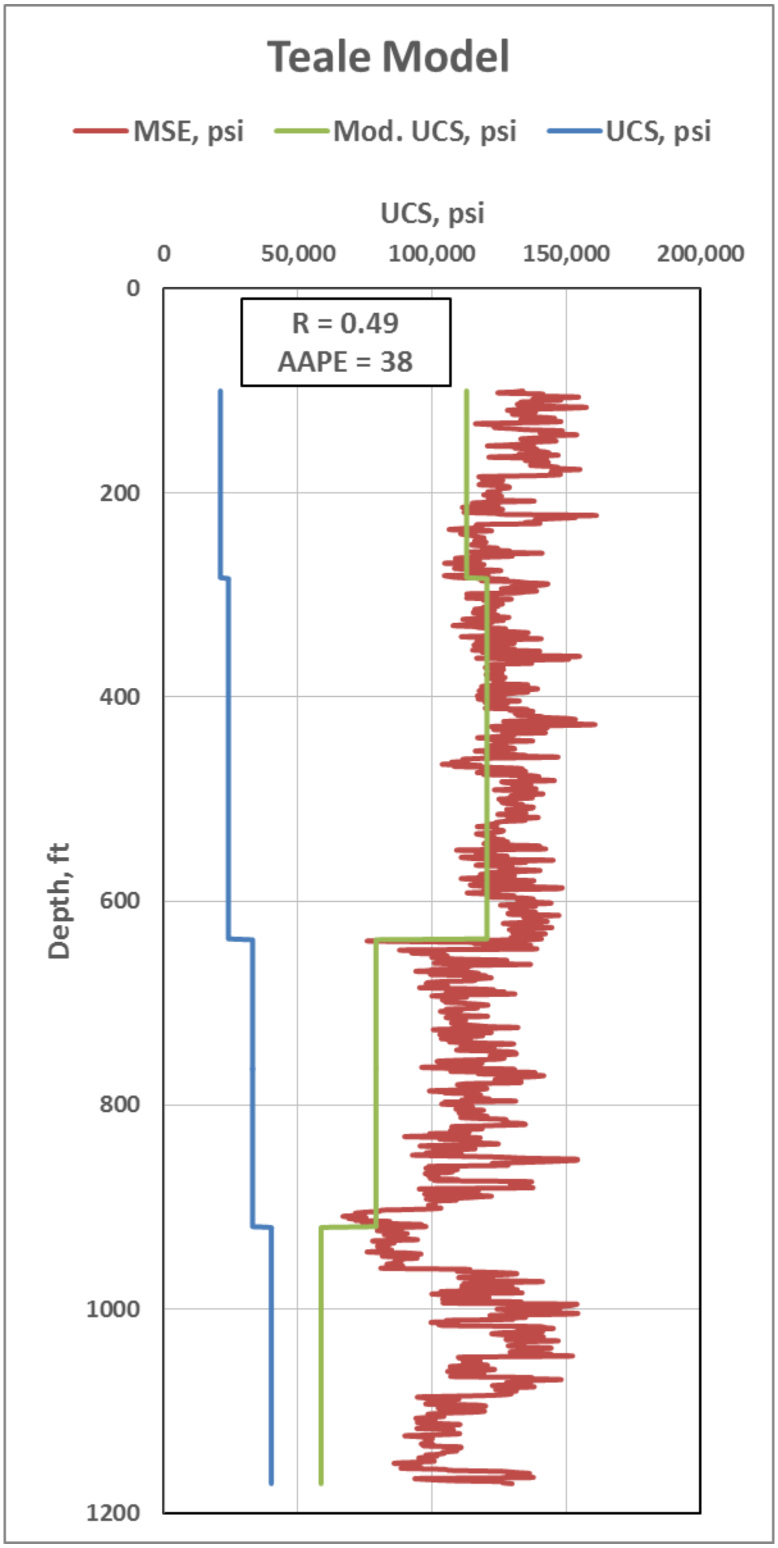

Figure 70: Comparison with Teale MSE model

Armenta (2008):

$$\boldsymbol{MSE = \frac{WOB}{A_B} + \frac{120\pi \times NT}{A_B \times ROP} - \frac{1{,}980{,}000 \times \lambda \times HP_B}{A_B \times ROP}} \tag{5.34}$$

$\boldsymbol{\lambda}$= bit hydraulic factor HP_B = bit hydraulic horse power

Armenta introduced the term next to the minus side to capture the effects of drilling hydraulics. The approach and the result is similar to Teale since the last newly introduced term is very small in value. The value for $\boldsymbol{\lambda}$ in Armenta charts was 0.005 and the result is shown in Figure.71.

All MSE models are compared in Figure 72 showing no significant difference and R2 between them is 99% (0.99). Figure 73 shows the comparison for all ROP models with Bingham and Bourgoyne & Young looking close while Maurer showed different results.

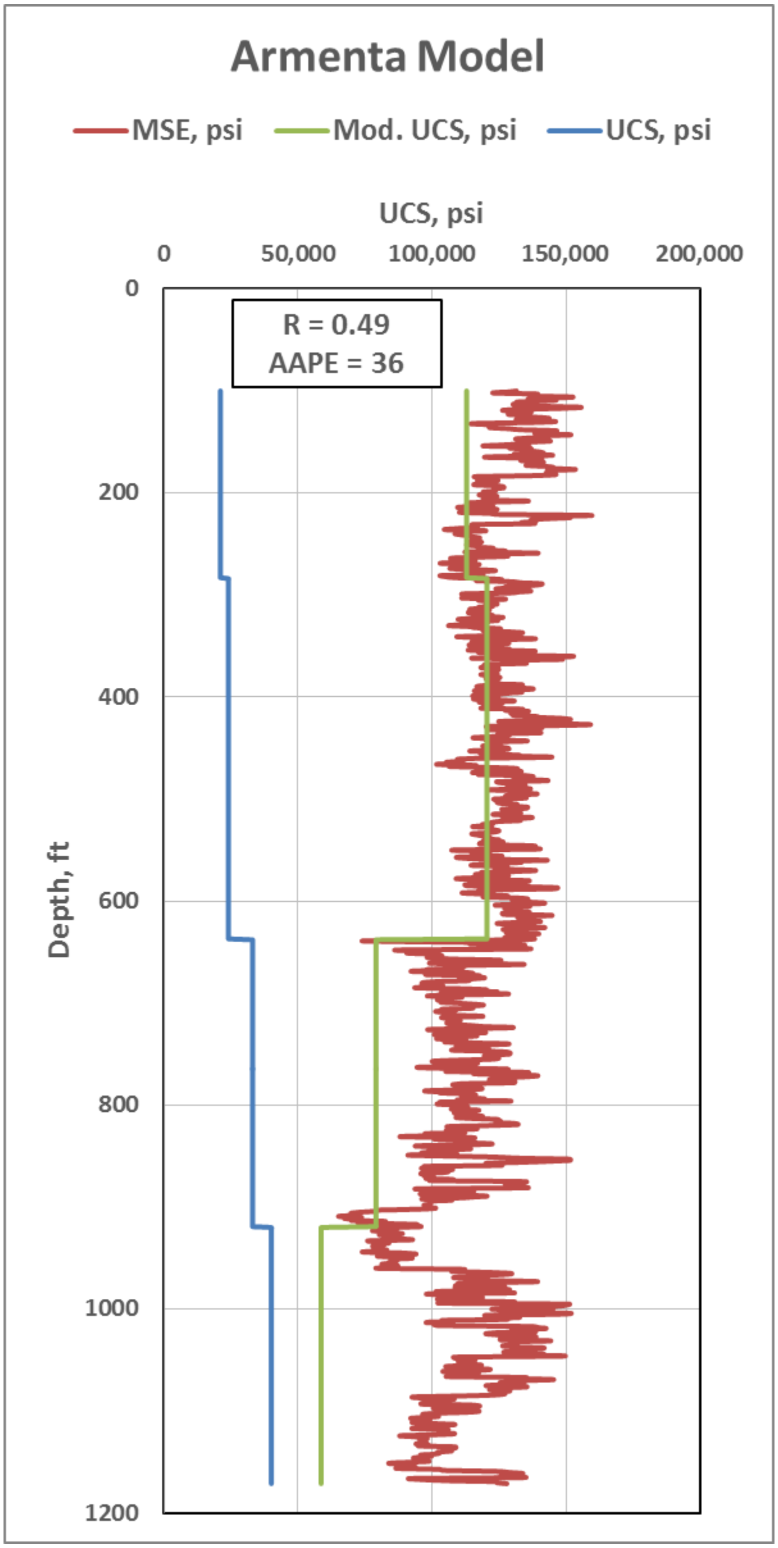

Figure 71: Comparison with Armenta MSE model

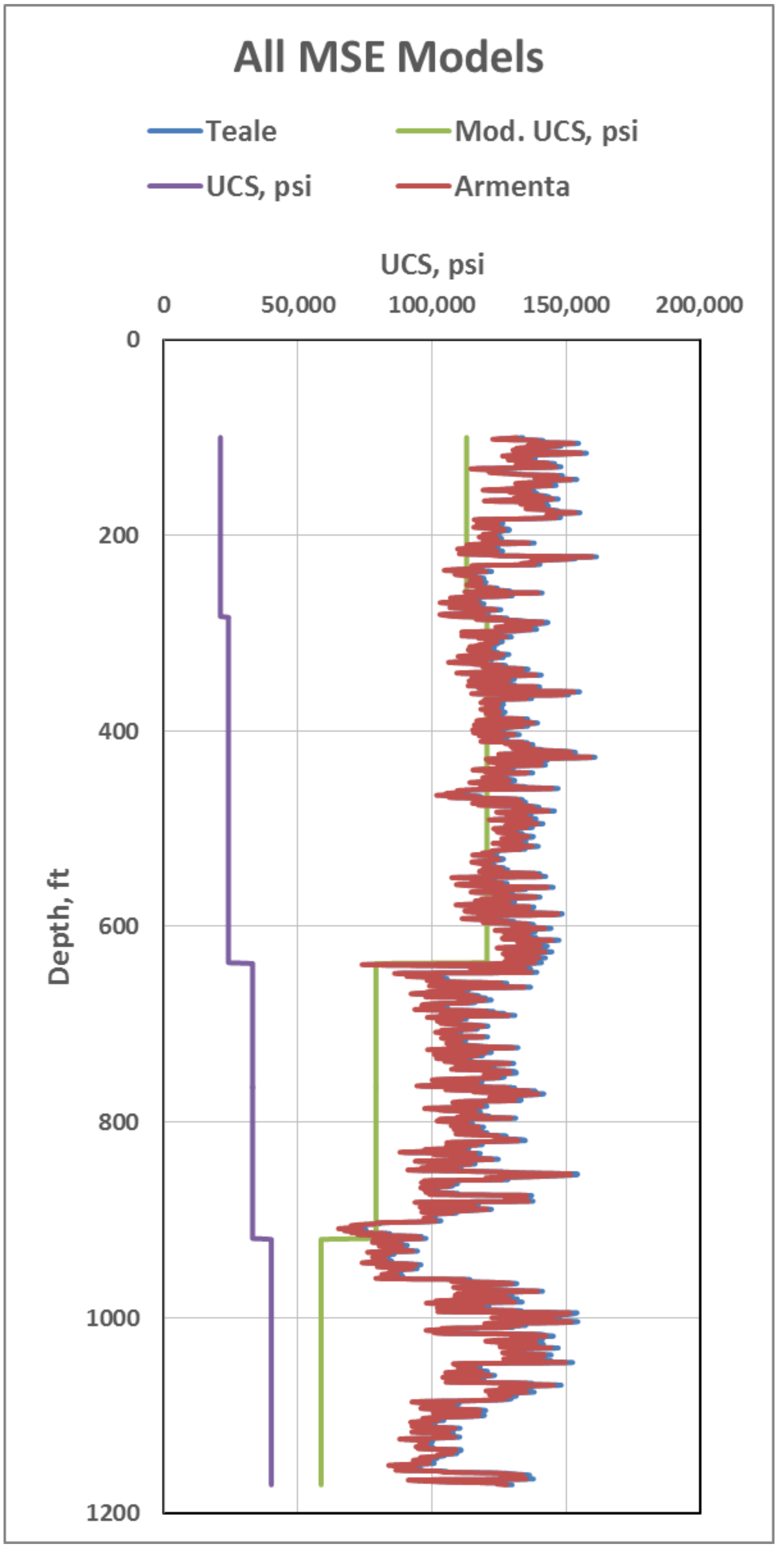

Figure 72: Comparison of all MSE models

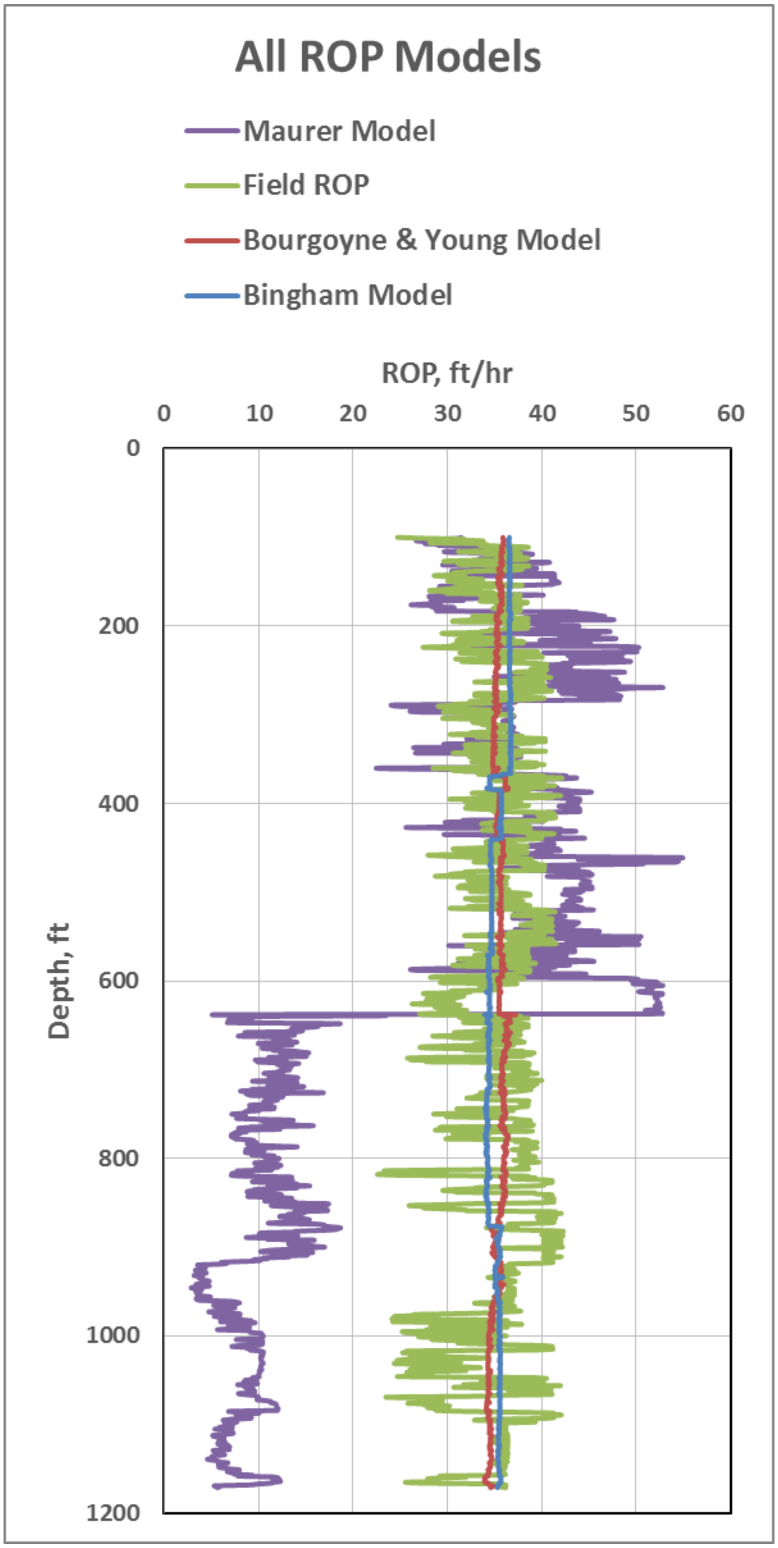

Figure 73: Comparison of all ROP models

In order to have a feeling for the data range of the ‘a’ and ‘b’ exponent obtained in this research, it was decided to compare it with other authors to see the variance between them. Table 13 below compares both bit and UCS exponents with other numbers found in the literature. Looking at the numbers below, they seem to fall in range with what previous others suggested, adding more confidence to the results obtained.

Table 13: Comparison of bit and UCS exponents 'a and b' with this research

Exponent	Author	Value
a (Bit)	Maurer	2
	Galle and Woods	0.6-1
	Bingham	0.64-2.85
	Warren	2
	Hareland	0.8-1.2
	This research	0.85
b (UCS)	Maurer	2
	Warren	2
	Hareland	1
	This research	1.036-1.169

5.5 Conclusion

The aim of this research is to understand the effect of drilling parameters and mud properties on rate of penetration in carbonate formations. In addition, a rate of penetration model is to be developed that capture the effects of both drilling and mud parameters. As shown in Chapter 4 there was a clear relation between drilling parameters and rate of penetration with most of them having a linear relationship expect weight on bit. For the mud parameters, yield point and viscosity didn't show any type of relation with the rate of penetration unlike the density, solid content and plastic viscosity which showed a clear relationship with a linear type in the first two and exponential type with the plastic viscosity.

The model developed in this research captured both drilling and mud parameters and had them all linearly dependent on the rate of penetration expect weight on bit and formation unconfined compressive strength. The model was developed on one well with R^2 of 0.87 and R of 0.93, then it was tested on other two wells scoring R^2 of 0.87 and 0.93 and R of 0.94 and 0.96. To validate the accuracy of this model, five other models were selected including both conventional ROP models and MSE models. All these five models gave a fitting that is much less than the proposed model which increase the confidence when using such a model. This model can be used in the future to predict the rate of penetration for different wells for the purpose of optimization.

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