# CHAPTER (1)

# INTRODUCTION

## 1.1 Background:

In Oil and Gas industry all considerations are focusing on the profit, which indicates reduction in expenditure. Drilling is one of the most expensive operations in oil exploration and development and all the phases in oil and gas industry, so all researchers in the drilling filed are working to optimize various parameters which can affect drilling cost. Rate of penetration (ROP) play as the master parameter, which has direct effect in drilling cost, therefore all models are utilized to predict the optimum rate of penetration (ROP) and during drilling operation, optimization of hydraulic at the drill bit is adopted to enhance bottom hole cleaning and to increase the rate of penetration. Generally, **drilling optimization** is the application of technology which yields a reduction of drilling costs associated with drilled hole, other definition of **drilling optimization** :"is Optimized drilling techniques have significantly reduced drilling cost. Results indicate that better data, more experience and confidence will result in greatly savings in the future". D. C-K CHEN (2004).The process involves the post appraisal of offset well record to determine the cost effectiveness of selected control variables. Which include mud type, hydraulics, bit type, weight on bit and rotary speed, formation hardness and differential pressure.

## 1.2 Types of Drilling Optimization Techniques:

There are many optimization techniques used in drilling

1. Cost per foot equation.
2. Time value of money.
3. Expected value method.
4. Lagrangian multiplier.
5. Multiple regression.
6. Confidence intervals.
7. Lagrange's interpolation formula.

The popular one of them is **cost per foot equation**; cost of footage drilled is the sum of 3 costs: Bit cost (cb), Trip cost (cr*tt) & Rig Operating cost for the time require to drill the footage (ΔD) (cr*(tb+tc).

$$Cf = \frac{Cb + Cr\,(tt + tb + tc)}{\Delta D} \quad \text{.......................} \quad (1.1)$$

## 1.3 Problem Statement:

Time is always money in the drilling operation. The concept of time taking for any drilling operation can be stated in term of drilling rate of penetration. Therefore estimation of the penetration rate is one of the essential parts of the drilling operation.

## 1.4 Objectives:

The main objective of the current project is to develop a computer program by using real field data from Sudanese oil field to determine:

- Optimum drilling parameters.
- Optimum rate of penetration.
- Minimum cost per foot.

## 1.5 Scope of project:

The scope of project is optimize of the parameters that will affect reduction of cost, drilling time and improve drilling efficiency by using **G**raphical **U**ser **I**nterface **(GUI).** This project involves the understanding and ability to deal with the **(GUI)** and also involves the understanding of modeling and optimize the ROP & important parameters. Proper understanding of all these parameters are important in order to keep this project work on the right track.

## 1.6 Factors Affecting Penetration Rate:

The factors which are influencing ROP can be classified in two main Groups:

1. Controllable Factors.

2. Environmental Factors.

Table 1.1 lists these factors. The controllable factors can be altered more easily than environmental factors. Because of economical and geological conditions, the variation of environmental factors is impractical or expensive. The number of factors hints at the complexity of the bit/rock interaction, something which is compounded by interdependence and nonlinearity in some of these effects, Fear, M.J. (1999). Since mud properties, such as type, density, etc, are all dependent on formation type, formation pressure, etc, mud properties are included in “Environmental Factors” in Table 1.1.

Table 1.1 factors proposed to affect ROP .Fear, M.J. (1999).

| Environment 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 |
| Bit size | Bit Hydraulic |
| - | Bit Nozzle Size |

## 1.7 Types of Drilling Bits:

There are several types of drill bits manufactured for different situations and conditions encountered during drilling operations. Basically there are two types of drill bits; these are the fixed-cutter bits, and roller-cone bits.

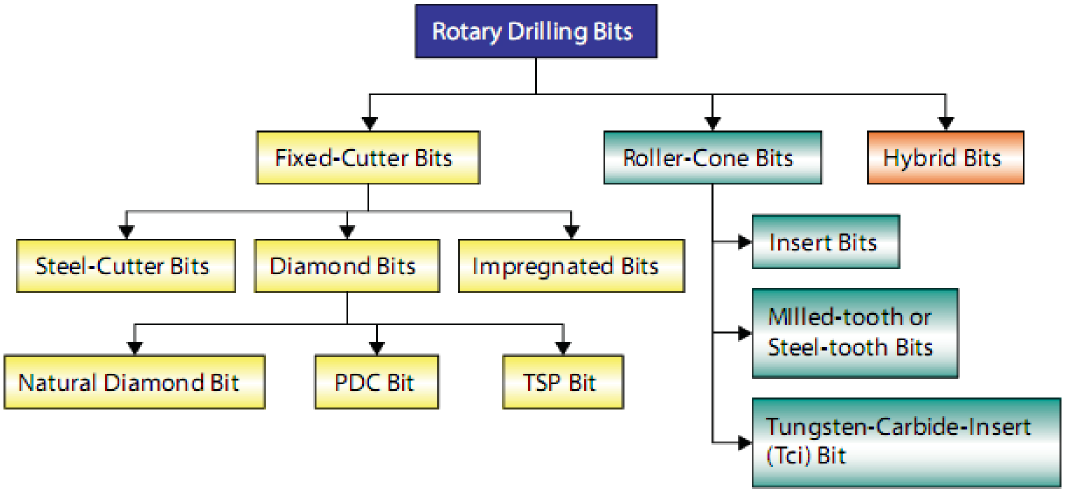


Figure 1.1 Classification of rotary drilling bits, Hossain (2015).

## 1.8 Rules of Drilling Bit Selection:

Several Rules of thumb are often used for initial bit selection:

**Rules of thumb #1**: If the formation hardness is known, then use the IADC charts (available in any handbook of IADC), or Bourgoyne et al., (1986).

**Rules of thumb #2**: Bit cost consideration plays a vital role for selecting initial bit type and features.

**Rules of thumb #3**: Selection of tri-cone roller bits. This is a good choice for an initial bit type, which is used for the shallow portion of the well. TCR bits are most versatile. In addition, use the longest tooth size possible.

**Rules of thumb #4**: Selection of diamond bits which perform best in non-brittle formations (having a plastic mode of failure) and bottom portion of well (due to longer bit life, minimizes high-cost tripping operations).

**Rules of thumb #5**: Selection of PCD drag bits, which perform best in uniform sections of carbonate formations (without thin stringers of brittle rocks or hard shale).

**Rules of thumb #6**: PCD drag bits should not be used in gummy formations (gluey shale, tending to cause bit balling.

**Rules of thumb #7**: Carefully evaluate a dull bit when it is removed from the well. Maintain carefully well-written records of the performance of used bits for future references.

## 1.9 Operating Conditions:

### 1.9.1 (Weight On Bit (WOB) & Rotary Speed):

A typical plot of penetration rate versus bit weight obtained experimentally with all other drilling variables held constant is shown in Fig. 1.2. No significant penetration rate is obtained until the threshold bit weight is applied (Point a). Penetration rate, then, increases with increasing values of bit weight (Segment a-b). As the weight on bit values are increased, a higher increase in ROP is observed (Segment b-c). However, after a certain value of bit weight, subsequent increase in bit weight causes only slight improvements in penetration rate (Segment c-d). In some cases, a decrease in penetration rate is observed at extremely high values of bit weight (Segment d-e). This type of behavior often is called bit floundering. The poor response of penetration rate at high values of bit weight usually is attributed to less efficient bottom hole cleaning at higher rates of cuttings generation or to a complete penetration of the cutting elements of the bit into the well bore bottom. At this weight on bit values, wear on the bit is extremely high, Hossain (2015).

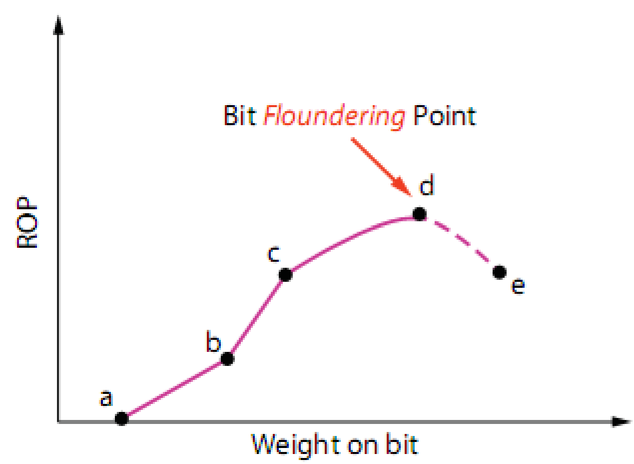


Figure 1.2 Typical response of penetration rate to increasing bit weight, Hossain (2015).

A typical plot of penetration rate versus rotary speed obtained with all other drilling variables held constant is shown in Fig. 1.3. Penetration rate usually increases linearly with an increase in rotary speed (Segment a-b). After a certain rotary speed value, the increase in ROP decelerates as rotation speed is increased (Segment b-c). After point-c, rotation speed has a very slight influence on ROP. The poor response of penetration rate at high values of rotary speed usually is also attributed to less wellborn stability and enlargement of the well bore, Bourgoyne (1990).

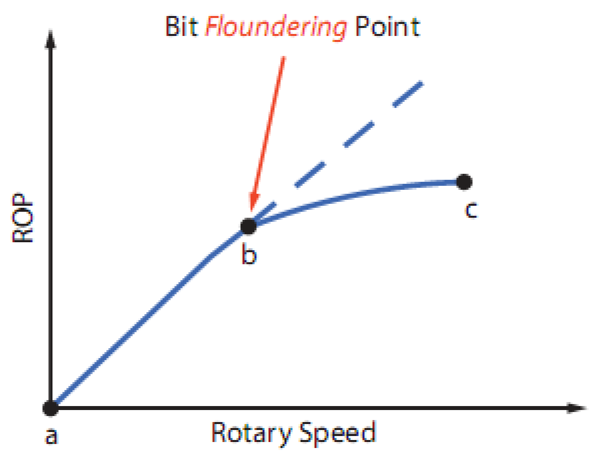


Figure 1.3 Typical response of penetration rate to increasing rotary speed, Hossain (2015).

### 1.9.2 Bit Tooth Wear:

Most bits tend to drill slower as the drilling time elapses because of tooth wear. The tooth length of milled tooth rolling cutter bits is reduced continually by abrasion and chipping. The teeth are altered by hard facing or by case-hardening process to promote a self-sharpening type of tooth wear. However, while this tends to keep the tooth pointed, it does not compensate for the reduced tooth length. The teeth of tungsten carbide insert-type rolling cutter bits and PDC bits fail by breaking rather than by abrasion. Often, the entire tooth is lost when breakage occurs. Reductions in penetration rare due to bit wear usually are not as severe for insert bits as for milled tooth bits unless a large number of teeth are broken during the bit run.

### 1.9.3 Bit Hydraulics:

Significant improvements in penetration rate could be achieved by a proper jetting action at the bit. The improved jetting action promoted better cleaning of the bit face as well as the hole bottom. There exists an uncertainty on selection of the best proper hydraulic objective function to be used in characterizing the effect of hydraulics on penetration rate. Bit hydraulic horsepower, jet impact force, Reynolds number, etc, are commonly used objective functions for describing the influence of bit hydraulics on ROP.

## 1.10 Drilling Cost Analysis:

Primarily drilling costs depend on well location and well depth. However, it is a function of manpower skills, and experience; operator, contractor, and service company's experience; geologic conditions; availability of drilling rigs and associated equipment; casing, cementing, of shore or on shore locations; equipment efficiency; well specification; and numerous other factors. In addition, there are many elements which contain the well cost. the major factors controlling the costs of drilling wells are the abnormal rig market conditions, well depth, diameter, casing design, well type (i.e. exploratory, development etc.), and well location. It is recognized that there are many factors affecting well cost which must be taken into consideration to accurately estimate the cost of a specific well. As a result drilling costs increase non-linearly with depth (Figure 1.4).

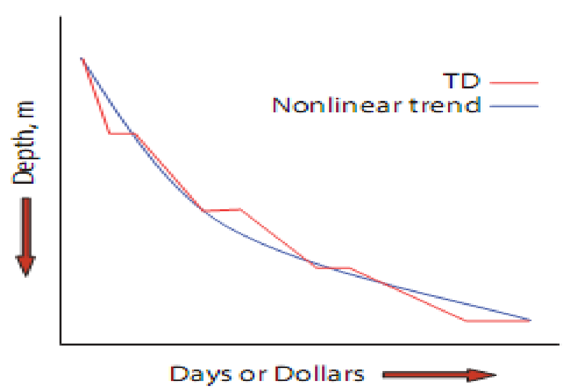


Figure 1.4 Drilling cost as a function of well depth, Hossain (2015).

### 1.10.1 Drilling Time Estimation:

An estimation of drilling time can be based on historical ROP data where the drilling program will be set for the area of interest. For a given formation, ROP is inversely proportional to both compressive strength and shear strength of the rock. In addition, rock strength tends to increase with depth of burial. This is due to the higher confining pressure caused by the weight of the overburden. When major unconformities are not present in the subsurface lithology, the penetration rate usually decreases exponentially with depth. Under these conditions, ROP can be related to depth, D as:

$$\frac{dD}{dt} = Ke^{-AD}$$

## 1.11 Project report Organization:

The current research consist of six chapters .The current chapter discusses the problem definition, Justification for carrying out the research, and the objectives.

In chapter two a brief summary of **previous studies** given the background for selection of procedures and techniques used to achieve optimum of the important parameters and estimate the drilling time of well eventually reducing the drilling cost for future wells.

Chapter three is **Methodology** & Procedures of the Project ,it is outline the entire research plan and synopsis **method**, **tools** and **other techniques** are used, also describe what date will be needed, what data gathering devices will be employing and analysis. Lastly, it shown time schedule (**Gantt Chart**).

In chapter four explain the **results** and **discussions**, also statistical results and graphs.

In chapter five **Conclusion** and **recommendations,** depend on the result and discussion, it can be summaries on some the main points of project.

The last chapter is **references, it** provides the list of references in the form of bibliography, it base on **harvard** system.

## 1.12 Layout:

Optimization of drilling parameters during drilling operations aims to optimize weight on bit, bit rotation speed for obtaining maximum drilling rate as well as minimizing the drilling cost in the area.

# CHAPTER (2)
# LITERATURE REVIEW

## 2.1 Theoretical Background:

There are many techniques that utilized for reduction of drilling operation cost. This can be achieved by optimize time of operation since time is always money in drilling operation. Time taken to drill any well in drilling operation can be represented by Penetration rate (ROP). Therefore Drilling Rate of Penetration plays main role in drilling optimization. Drilling Model must be developed to come out with rate of penetration.

Drilling models are always find the best mathematical relationship between ROP and other drilling parameters that have important effect on it. Because of the uncertain drilling variables there is no direct or exact mathematical relation for rate of penetration and other drilling parameters, and also their relationship are complex and nonlinear. Penetration rate can be affected by many parameters such as:

Weight on bit (WOB), bit hydraulic, bit type, rotary speed (N), formation characteristic and mud properties etc, are the parameters affecting rate of penetration. Here, are lots of models that have been proposed for rate of penetration such as Bourgoyne and Young model, Artificial Neural Network (ANN), Bingham model and Warren model, etc.

First step is to review the background in several rate of penetration models but before that there is one method lowering drilling cost, which is cost per foot analysis. That aimed to optimize the rate of penetration. It is based on the optimum drilling operation condition of bit run and the criteria of bit selection or respected bit selection. It can estimate the cost per foot as follow:

$$Cf = \frac{Cb + Cr(tt + tb + tc)}{\Delta D}$$

For this equation Cf is the cost per foot drilled cost per unit depth ($/ft), Cr is the fixed operating cost per time ($/ft), Cb is bit cost ($), $\Delta D$ is the drilled depth (ft) tr is bit rotating time (*h*r), tt is the total trip time (*h*r), *c* time pipe connection (*h*r).

If drilling rate is high the drilling cost will be reduce from the drilling cost equation so ROP can play main role to reduce the cost . So, we can choose one of the models to optimize ROP. There are common models used to optimize ROP.

## 2.1 ROP Models:

### 2.2.1 Overview of ROP Correlation Models:

**Warren, T.M (1984)** developed a model for predicting ROP for roller-cone bits under low-borehole-pressure conditions. This model accounted for both cuttings generation and cuttings removal. Drilling data obtained under high- borehole-pressure conditions were analyzed to determine the reasons of the reduction in ROP as the borehole pressure increases. In some cases, the reduced ROP is caused by a buildup of rock debris under the bit. When this occurs, the ROP can be improved by an increased level of hydraulics. In other cases, the reduction in ROP seems to be caused by a local catering effect that is much less responsive to increases in hydraulics. Comparison of model predictions to the observed ROP can help to identify the mechanism that limits the ROP and provide insight into ways to improve it, Batee (2010).

$$R = \left(\frac{as^2db^3}{N^bW^2} + \frac{c}{Ndb}\right)^{-1}$$

Dimensional analysis was used to isolate a group of variables consisting of the modified impact force and the mud properties to incorporate into above equation to account for the cutting removal .These factors were combined with equation until an equation was obtained that matched the experimental data .The resultant expression for ROP is, Batee (2010):

$$R = \left(\frac{as^2db^3}{NW^2} + \frac{b}{Ndb} + \frac{cdb\gamma f\mu}{Fjm}\right)^{-1}$$

**Bingham model** is a simple model which is a modification of Maurer Model (an experimental model which is applicable to low value of weight on bit (W) and rotary speed (N). Also this is a simple model .This model neglects the depth of drilling so the answer often has less reliability.

$$R = K\left(\frac{W}{db}\right)^{a5} * N^{e}$$

**Bourgoyne and Young's model (1991)** introduces penetration rate as a function of eight variables such as sediments compaction and strength, pore pressure, bit weight, rotary speed, bit hydraulics, teeth wear, etc. The model mathematically is expressed by: Batee (2010)

$$\boldsymbol{R = f1 \times f2 \times f3 \times f4 \times f5 \times f6 \times f7 \times f8}$$

Where, ROP is rate of penetration ($ft/hr$), 1 is the function of the formation drill ability (mud type, bit type, formation strength), symbolize the impact of compaction on the penetration rate represent by $f2$, $f3$& $f4$, signifies the overbalance on ROP, $f5$& $f6$ respectively model the effect of bit weight and rotary speed on ROP, effect of tooth wear and bit hydraulic represent by $f7$&$f8$ respectively.

BYD creators proposed multiple regression method to find the unknown coefficients, but applying multiple regression method is not reliable that it can procedure to meaningful results physically, and also number data point limit is affecting this method. So, recently there are many new mathematical techniques applied to calculate these unknown coefficients, to reach the meaningful result. Example of these methods is Nonlinear least square data fitting with trust –region method is a technique applies to the problem.

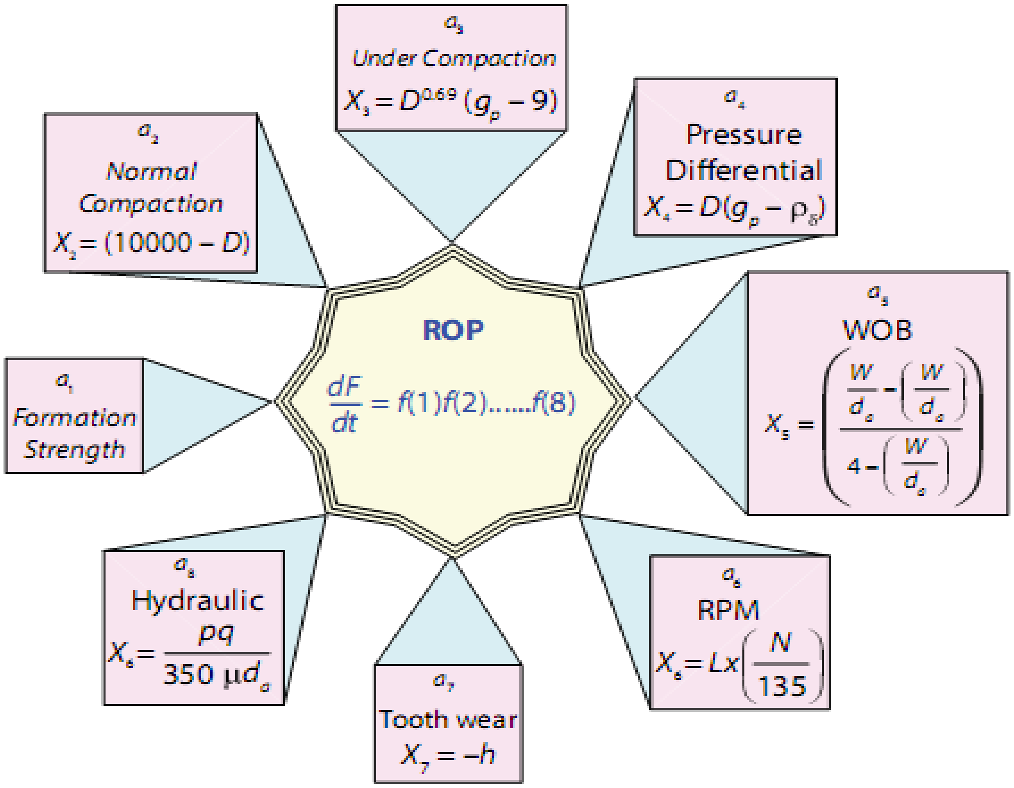


Figure 2.1 General rate of penetration equation of B&Y, Hossain (2015).

**Bahari** (2007) Writing computer program and applied three methods rather than multiple regression method to solve Bingham's constants on nine wells data of Khangiran gas field, he compared result of each method and that trust-region method is the best.it can be applied easily to predict penetration rate when a few data points are present and when the drilling parameter are not in the recommended ranges.

**Bahari et al** (no date), they proposed method solves two Deficiencies, physically meaningless coefficients, and the decrease in accuracy. In their method, their practical data sets were nine wells of "Khangiran" Iranian gas field, they applied Genetic Algorithm GA to determine constant coefficient of Bourgoyne and Young model. Simulation result confirm that suggested approach not only provides meaningful results but also leads to more accuracy in comparison with conventional methods.

In both papers Bahari Used Bourgoyne and Young Model to Forecasting the Rate of Penetration.

**Bataee et al** (2010): calculate and predict the proper model of ROP for roller cone bit and PDC bits in each well by using the ROP models (Bingham model, bourgoyne and young model, warren model) and verify the validity of each model with field data .the application of present study are predicting the proper penetration rate, optimizing the drilling parameter, estimate the drilling time of well eventually reducing the drilling cost for future wells.

**Bielstein and Geiorge** (1950) recorded preliminary tests to determine the effect of various factors affecting the rate of penetration of rock bits. They also established the importance of the number and design of cutting elements in rate of penetration. Findings that the magnitude of the various effects on the rate of penetration varies with changes in the type of formation drilled.

The effect of hydraulic factors affecting the rate of penetration is explored

. Effects of rotary speed and bit weight were investigated, and it was found that the rate of penetration increased with increasing rotary speed and bit weight, with the rate of change in the two factors being principally a function of the formation being drilled.

**Carlos M. C. Jacinto, et al** (2013), used Bayesian Network (BN) inference approach for targeting the elicitation process and subsequent combination of models; and a Dynamic Evolving Neural-Fuzzy Inference System (DENFIS) in their research to optimization of the cost of drilling wells in environments of high complexity and risk such as those related to the pre-salt region offshore Brazil.

In order to reduce costs it is necessary to accurately plan offshore oil drilling operations. The time required to successfully drill a well has to be estimated fairly precisely, since most of the costs associated are tied to the rental of equipment required for the operation as reported by Gandelman (2012); however, each operation has unique properties that make this task highly difficult. Many properties vary, such as rock type, rock porosity, gas presence, pressure, drill bit wear rate among others. All these properties affect the ROP, as well as many other parameters which are controlled by a drilling operator: weight on bit(WOB), revolutions per minute(RPM), bit type, bit diameter, bit wear rate, hydraulic horsepower per square inch(HSI).

Most of the work in the planning phase is restricted to adjusting bit type and diameter, RPM and WOB in order to achieve an acceptable ROP. To optimize this work many systems using artificial neural networks (ANN) were proposed in the past to predict the rate of penetration (ROP) for the project planning phase such as Bilgesu et al. (1997) and even choose automatically some parameters such as RPM and WOB in Fonseca et al. (2006). Unfortunately for the available data on the Brazilian pre-salt layer these systems did not achieve a reliable result due to the poor quality and scarcity of data. To overcome these problems they investigated two alternative approaches: a Bayesian Network (BN) inference approach for targeting the elicitation process and subsequent combination of models; and a Dynamic Evolving Neural-Fuzzy Inference System (DENFIS) Carlos M. C. Jacinto, et al (2013).

**Eckel** (1967) was able to establish from laboratory and field experience that the rate of drilling using mud was increased from 30 to 70 percent of those obtainable with water under the same conditions. Eckel (1967) further stipulated that viscosity is a significant factor affecting the rate of drilling. Eckel (1967) used oil emulsion in his experiments and he observed that the rate of drilling was improved due to their lubricated properties.

**Eckel** (1967) concluded that mud rheological properties have significant effect on the rate of penetration.

**Fear** (1999), produce numerical correlation between ROP and drilling parameters after that use this correlation to generate recommendations for maximizing ROP. The data used are:

- mud logging
- geological information
- bit characterization

(bit/rock) inter action considered to minimize the general cost of drilling because it significantly affected.

In addition to torque and drag managed dependent on bit type and down hole tools which chosen to raise ROP with the new drilling technologies. In summary rock properties that influence ROP include: at least: mineralogy, strength, density, porosity and permeability. Also weight on bit (WOB), rotary speed, flow rate independence between mechanical and hydraulic drilling.

Environmental factor affected in ROP are: Formation properties and types, mud density types and properties.

Controllable factors affected in ROP are: Bit wear state, deign, rotary speed, hydraulic horse power, weight on bit, flow rate and bit nozzle.

Application of method**:** It is used as check list, so data assembled as to minimize ROP by the effect of variable of both environmental and controllable factors.

**Galle et al.,** (1969) presented a pioneer work that created a major breakthrough in drilling technology, mainly when referring to optimization aspects. They assumed that rate of penetration was affected by only two parameters, weight on bit and rotary speed. In their paper, also, it is assumed that all other variables involved, like bit selection, hydraulics, drilling fluid properties, etc., were properly selected. They defined an analytical model to predict rate of penetration (ROP) as a function of weight on bit, rotary speed, type of formation, and bit tooth wear.

**Gregorio** (May 2004) evaluate the benefits and practical application of the drilling simulation technology. They have found in the literature that is possible predict the drilling performance on the basis of a combination of theoretical and lab drilling models. Different companies are developing and using drilling simulators in the planning and drilling of oil wells. The results show that a drilling simulator can accelerate training, increase the use of the best technology, and shorten the drilling learning curve. After a set of wells is drilled, the experience can be captured and retained. The drilling simulator can generate a complete model of the drilling process, so the engineers can run multiple scenarios quickly and update the plans with the new data to predict the consequences of their decisions. The research has shown the software accuracy in the prediction of the unconfined rock strength based on drilling and lithology data (compared with unconfined rock strength estimated from electric logs).

The drilling parameters analysis showed that WOB and ROP are critical in drilling optimization. The research shows that using the maximum WOB available and reducing rotational velocity of the bits increase their performance in the Aloctono block.

The use of DROPS® drilling simulator software as an optimization tool allowed selection of new mud and bit programs with better cost per meter, ROP, and drilling time.

**Humphrey** (2013), optimum conditions for drilling were determined by estimating pore pressure and fracture pressure from conductivity data, selecting a suitable mud with an appropriate density based on the result of the conductivity data analysis, studying the rheological properties of mud samples (3 samples), calculating the pressure losses in the mud circulatory system and finally applying the maximum horsepower criterion for optimization.

Based on the results of conductivity data analysis, experimental analysis of the drilling mud rheology and pressure loss calculation in the mud circulatory system, conditions for optimum hydraulic horsepower across the drill bit in the problematic zone is presented in his case study. His study shows that pressure loss in the mud circulatory system depends on the mud and the circulating flow rate. Also, the operating conditions obtained in his study shows that the flow rate exceeds the minimum flow rate required for drill cuttings removal. One unique aspect of his project work is the integration of experimental work designed to generate rheological data for theoretical computation.

The disadvantage of this project work that is focused on the application of optimization using the maximum horsepower criterion only in an over pressure zone for bottom hole cleaning and for showing the effect of mud rheology on pressure losses in a mud circulatory system.

**Irawan**, et al (2012), used Bourgoyne and Young model in there project in order to derive equations to perform the ROP estimation using the available input data. This model has been selected because it is considered as one of the complete mathematical drilling models in use of the industry for roller-cone type of bits (Bahari and Baradaran, 2007).

The rate of penetration for the field had been predicted based on constants for every data vs. Depth. Finally, optimized weight on bit had been calculated for several data points. In the end, drilling simulator (Drill-Sim 500) was used to prove the results based on actual field data.

The penetration model for the field is constructed using the results from statistical method. In the end, the result from analysis is used to determine optimum values of weight on bit that give optimum drilling operation.

**Mostofi** et al (2010) used two term ROP model (1981), three term ROP model for tri cone bit (1987) and Horeland and Hoberock modified model (1993) to include differential pressure effect, bit tooth wear, hole cleaning issue in the analysis. In their model 2 sets of information required to develop it, Geological Drilling Log GDM and bit constants, linearization method seems to provide better results. And then best bit runs are introduced.

**Roman** and David (no date**)**, He reviewed papers share one common failing: The technique used to optimize drilling are too limited in scope. They are concerned only with finding the weight, speed, time schedule

That corresponding to a minimum value of the drilling cost per foot for each bit used .He seek in his two part paper to remedy that failing by developing techniques which are less limited in scope and by demonstrating the superiority of a method which established an optimal policy for the entire well rather than for each bit used .Part one explore two methods. The first method minimizes the cost per foot drilled during a bit run ,and the second the cost of selected interval .Part two examine the third method ,which minimizes the cost over a series of intervals .These techniques may be selected in accordance with the amount of drilling data available.

Equation used in this model is suggested by Galle and woods, they are not capable of explicitly accounting for changes in mud properties, hydraulics or bit type.

**Reza** et al., (1986) developed a drilling model using dimensional analysis. The parameters included in the three equations of penetration rate, rate of bit dulling and rate of bearing wear are weight on bit, rotary speed, flow rate, bit diameter, bit nozzle diameter, bearing diameter, mud kinematics viscosity, differential pressure, temperature, and heat transfer coefficient. They developed dimensionless models for roller cone, PDC and diamond bits.

**Wilson**, D.C et al.,( 1972) presented optimization techniques for minimizing drilling costs by restricting the number of parameters to be optimized to two, namely, the weight on the bit and the rotary speed. In this study, three methods of varying complexity have been developed. The first method seeks to minimize the cost per foot drilled during a bit run. The second method minimizes the cost of a selected interval, and the third method minimizes the cost over a series of intervals. The methods are listed in order to increase complexity. It was found that each of the methods gave a worthwhile cost saving and that the saving increased as the complexity of the method increased. The data requirements for the method increased with increasing method complexity.

**Winters, W.J et al.,** (1987) developed a model, which relates roller cone bit penetration rates to the bit design, the operating conditions, and the rock mechanics. Rock ductility is identified as a major influence on bit performance. Cone offset is recognized as an important design feature for drilling ductile rock. The model relates the effect of cone offset and rock ductility to predict the drilling response of each bit under reasonable combinations of operating conditions. Field data obtained with roller cone bits can be interpreted to generate a rock strength log. The rock strength log can be used in conjunction with the bit model to predict and interpret the drilling response of roller cone bits.

## 2.3 Summary of Literature Review:

As we can see most of pervious literatures used, Bourgoyne and young model, warren model and artificial neural networks (ANN) for predicting optimum ROP with more accuracy than Bingham model because this model neglects the depth of drilling so the answer often has less reliability. The validity of each model varying according to available field data.

Sony used optimum ROP to determine optimum weight on bit, and that exactly oppositely to our work.

In all above literatures there is no one use GUI for calculating ROP so we decided to use it for developing program that calculating most of the related parameters to reach optimum ROP.

# CHAPTER THREE

# METHODOLOGY

This chapter demonstrates the methodology followed to build the program achieved including rock-bit interaction models, hydraulic models, drilling softwares and simulator software by developing drilling optimization software through utilizing Graphical User Interface (Matlab GUI) techniques for optimization and PAYZONE drilling simulator for comparison and verification.

## 3.1 Research Methodology:

This project will apply GUI Techniques to predict the rate of penetration (ROP), Hydraulic parameters, trip and rotating time and to select the bit according to the cost of the drilling. The research methodology procedures is illustrated in the following chart:

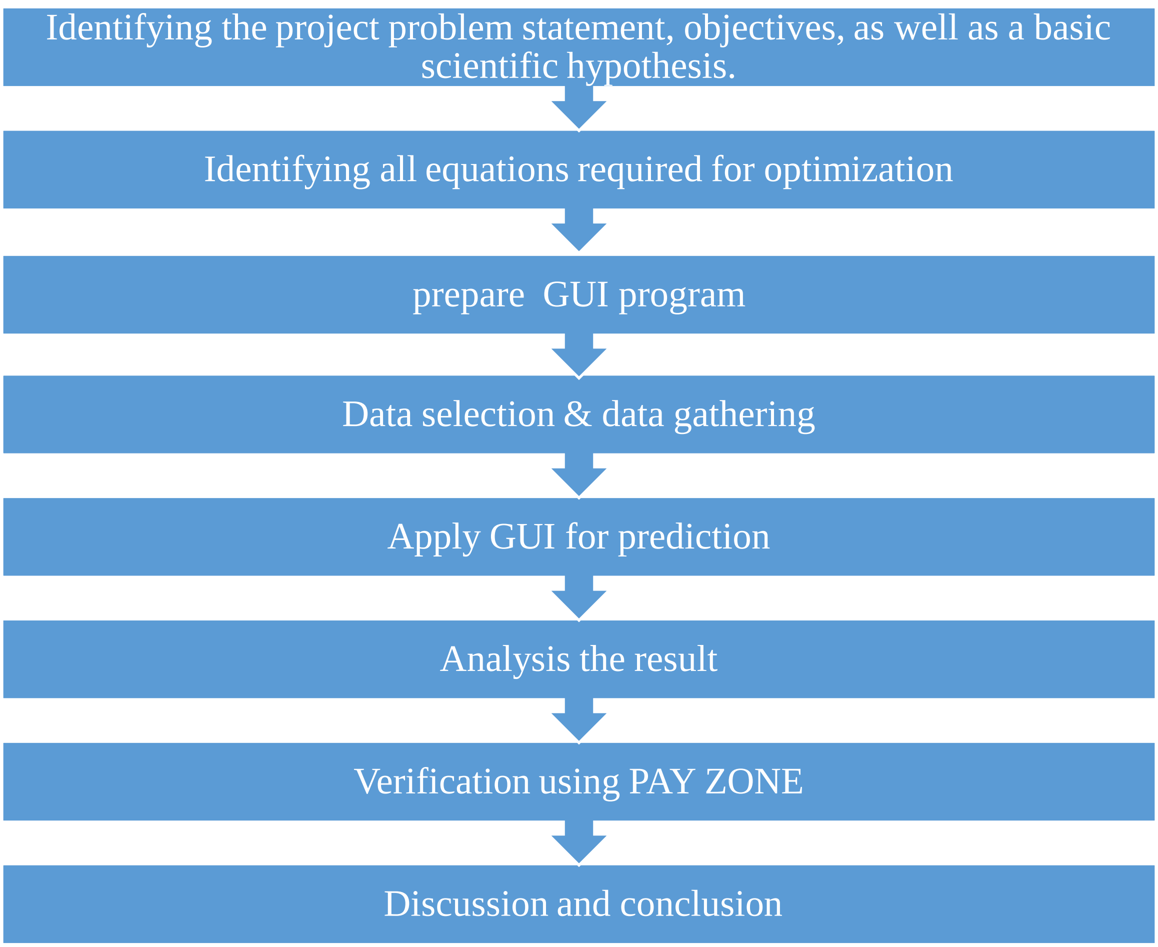


Figure 3.1 Research Methodology flow chart

## 3.2 GUI program preparation

**GUI** (**G**raphical **U**ser **I**nterface) is a "means by which people and computers communicate with each other". One can make an analogy between a computer system's GUI and a car's steering wheel. The wheel directly binds the driver to the operation and functionality of the vehicle. When driving, a driver should not have to concentrate on the steering wheel. In the same way, the GUI binds the user of the computer system to operation and potential of the computer system. A good GUI design removes the impediment of communication with the computer system and allows the user to work directly on the problem at hand.

In computer science terms, the GUI is a visual operating display that the monitor presents on the monitor to the computer operator. More specifically, a GUI is a specification for the look and feel of the computer system. GUI usually have common characteristic such as windows, icons, menus, and push-buttons (WIMP).

Identify the equations require for building program which can be divided for many parts as showing in next items.

### 3.2.1 Optimization of Hydraulics, Rabai (2011) :

Inadequate hole cleaning can lead to a number of problems, including hole fill, packing off, stuck pipe, and excessive hydrostatic pressure. Drill cuttings in the hole cause wear and tear of the drill string and also reduce the rate of penetration, thereby increasing the cost and time for drilling; hence, there is need to design a system that will efficiently remove the drill cuttings, transport them to the surface in a cost effective manner, prepare an appropriate drilling mud and maximize the hydraulic horse power at the drill bit, Humphrey (2012).

Surface loss (P1) = $E\ x\ \rho^{0.8} x\ Q^{1.8}\ x\ PV^{0.2}$……….…. (3.1)

Table 3.1 pressure loss equations for Bingham and power law Model, Rabia

| Model | | Laminar flow (V′< Vc) | Turbulent flow (V′> Vc) |
|---|---|---|---|
| **Bingham** | Pipe flow | $P = \frac{L \times PV \times V'}{90{,}000 \times D^2} + \frac{L \times YP}{225 \times D}$ | $P = \frac{8.91 \times 10^{-5} \times \rho^{0.8} \times Q^{1.8} \times (PV)^{0.2} \times L}{D^{4.8}}$ |
| | Annular flow | $P = \frac{L \times PV \times V'}{60{,}000 \times De^2} + \frac{L \times YP}{225 \times De}$ | $P = \frac{8.91 \times 10^{-5} \times \rho^{0.8} \times Q^{1.8} \times (PV)^{0.2} \times L}{(Dh - OD)^3 (Dh + OD)^{1.8}}$ |
| **Power law** | Pipe flow | $P = \frac{KL}{300D} \times \left(1.6V' \frac{1.6V' (3n+1)}{(D \times 4n)}\right)^n)$ | $P = \frac{8.91 \times 10^{-5} \times \rho^{0.8} \times Q^{1.8} \times (PV)^{0.2} \times L}{(Dh - OD)^3 (Dh + OD)^{1.8}}$ |
| | Annular flow | $P = \frac{KL}{300De} \times \left(\frac{2.4V' \times (2n+1)}{(De \times 3n)}\right)^n$ | $P = \frac{8.91 \times 10^{-5} \times \rho^{0.8} \times Q^{1.8} \times (PV)^{0.2} \times L}{(Dh - OD)^3 (Dh + OD)^{1.8}}$ |

Where the average velocity of flow in the pipe for both Power law and Bingham calculating from:

$$V' = \frac{24.5Q}{D^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Average velocity of flow in the annular for both Power law and Bingham calculating from:

$$V' = \frac{24.5Q}{Dh^2 - OD\text{^}2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Critical velocity of pipe flow for Power law model:

$$Vc = \left(\frac{5.82 \times 10^4 \times K}{\rho}\right)^{\frac{1}{2-n}} \times \left(\frac{1.6 \times (3n+1)}{(D \times 4n)}\right)^{\frac{n}{1-n}} \quad \ldots\ldots (3.4)$$

Critical velocity of annualr flow for Power law model:

$$Vc = \left(\frac{5.82 \times 10^4 \times K}{\rho}\right)^{\frac{1}{2-n}} \times \left(\frac{1.6 \times (3n+1)}{(De \times 4n)}\right)^{\frac{n}{1-n}} \quad \ldots\ldots (3.5)$$

Critical velocity of pipe flow for Bingham model:

$$Vc = \frac{97PV + 97\sqrt{PV^2 + 6.2\rho De^2 YP}}{\rho De} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Critical velocity of annular flow for Bingham model:

$$Vc = \frac{97PV + 97\sqrt{PV^2 + 6.2\rho De^2 YP}}{\rho De} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Where De = Dh-DO

Pressure drop across bit = Pbit = Pstandpipe – system loss…. (3.8)

Nozzle Selection:

$$TFA = (0.00096 \times Q)\sqrt{(\frac{\rho}{pbit})} \ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

$$dn = 32\sqrt{(\frac{4TFA}{(3\times\pi)})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.10)$$

$$Vn = 33.36\sqrt{(\frac{Pbit}{\rho})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

## 3.2.2 Hydraulic Criteria, Rabia:

Table 3.2 Hydraulic Criteria

| | |
|---|---|
| Maximum Bit Hydraulic Horsepower | $k = \frac{Pc_i}{(Q_i)^n}$ <br> $Pbit = \frac{n}{n+1} \times Ps$ <br> $\mathrm{BHHP} = \frac{\mathrm{Pbo} \times \mathrm{Qopt}}{1714}$ <br> $\mathrm{IF} = \frac{\mathrm{Qopt} \times \sqrt{(\rho \times \mathrm{Pbo})}}{58}$ <br> $\mathrm{TFA} = 0.0096 \times \mathrm{Qopt} \times \sqrt{(\frac{\rho}{\mathrm{Pbo}})}$ <br> dno= $32 \times \sqrt{(\frac{4\times\mathrm{TFA}}{3\times\mathrm{pi}})}$ |
| Maximum Impact Force | $Pbit = \frac{n}{n+2} \times Ps$ <br> $IF = \frac{Q \times \sqrt{\rho} \times Pbit}{58}$ <br> $\mathrm{BHHP} = \frac{\mathrm{Pbo} \times \mathrm{Qopt}}{1714}$ <br> $\mathrm{IF} = \frac{\mathrm{Qopt} \times \sqrt{(\rho \times \mathrm{Pbo})}}{58}$ <br> $\mathrm{TFA} = 0.0096 \times \mathrm{Qopt} \times \sqrt{(\frac{\rho}{\mathrm{Pbo}})}$ <br> dno= $32 \times \sqrt{(\frac{4\times\mathrm{TFA}}{3\times\mathrm{pi}})}$ |

Slip velocity:

$$Vs = 174.7dp \times \frac{(\rho p - \rho f)^{0.667}}{\rho f^{0.333} * \mu e^{0.333}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

$$\mu e = \left[\left(2.4v' \frac{2n+1}{(Dh-ODp)*3n}\right)\right)^n \times \frac{200K(Dh-ODp)}{v'} \ldots\ldots (3.13)$$

Transport velocity:

$$Vt = Va - Vs \quad \text{......} (3.14)$$

Drill Cuttings Concentration:

$$Ca = (\frac{1}{60}) \times \frac{(ROP \times Dh^2)}{(Va - Vs) \times (Dh^2 - ODp^2)} \quad \text{......} (3.15)$$

### 3.2.3 Optimization of Bit Selection:

$$J2 = \left(\frac{60}{N}\right)^{H1} (\frac{1}{1+\frac{H2}{2}}) \left[\frac{(\frac{W}{db})_m - (\frac{W}{db})}{(\frac{W}{db})_m}\right] \quad \text{......} (3.16)$$

$$\tau H = \frac{t_b}{J2 h_f \left(1 + \frac{H2}{2} h_f\right)} \quad \text{......} (3.17)$$

$$J3 = \left(\frac{60}{N}\right)^{B1} \left(\frac{4db}{W}\right)^{B2} \quad \text{......} (3.18)$$

$$t\text{b} = \boldsymbol{J2}\ \tau\text{H}\ h\text{f}\ (1 + \left(\frac{H2}{2}\right) h\text{f}) \quad \text{......} (3.19)$$

$$\frac{db}{dt} = \frac{1}{\tau B} \left(\frac{N}{60}\right)^{B1} \left(\frac{W}{4db}\right)^{B2} \quad \text{......} (3.20)$$

### 3.2.4 Optimization of Bit Weight and Rotary Speed:

Bearing Failure:

Rotating time calculation:

$$Tr = \frac{bB}{NW^{1.5}} \quad \text{......} (3.21)$$

Tooth wear:

$$Hf = -\frac{1\sqrt{1 + 2C1 \frac{Tr\left[10^3 Af\,(PN + QN^3)\right]}{-D1\,W + D2}}}{C1} \quad \text{......} (3.22)$$

Footage drilled:

$$\Delta D = Y = (\frac{K(W - M)N^{\lambda}(-DW + D2)}{10^{-3} Af(PN + QN^3)} \left[\frac{C1}{C2} Hf + \frac{C2 - C1}{C2^2} \ln(1 + C2Hf)\right]$$

$$\text{......} (3.23)$$

Tooth Failure:

$$Tr = (\frac{(-DW + D2)}{10^{-3} Af\,(PN + QN^3)} \left[1 + \frac{C1}{2}\right] \quad \text{......} (3.24)$$

Footage drilled:

$$\Delta D = Y = (W - M)N^{\lambda} Tr \left\{\frac{2K}{2 + C1} \left[\frac{C1}{C2} + \frac{C2 - C1}{C2^2} \ln(1 + C2)\right]\right\} \quad \text{......} (3.25)$$

### 3.2.5 ROP models:

Mentioned in literature review's chapter , where : Irawan et al (2012).

$$f1 = e^{a1} \ldots\ldots (3.26)$$

$$f2 = e^{a2}(1000 - D) \ldots\ldots (3.27)$$

$$f3 = e^{a3} D^{.69}(gp - 9) \ldots\ldots (3.28)$$

$$f4 = e^{2.303a4} D(gp - pc) \ldots\ldots (3.29)$$

$$f5 = \left[\frac{\frac{w}{db} - \left(\frac{w}{db}\right)t}{4 - \left(\frac{w}{db}\right)t}\right]^{a5} \ldots\ldots (3.30)$$

$$f6 = \left(\frac{N}{1000}\right)^{a6} \ldots\ldots (3.31)$$

$$f7 = e^{a7(-h)} \ldots\ldots (3.32)$$

$$f8 = \left(\frac{Fj}{1000}\right)^{a8} \ldots\ldots (3.33)$$

### 3.2.6 Prediction of drilling cost, drilling rate and drilling time based on depth:

Drilling cost Tend to increase **exponentially** with depth.

$$c = ae^{bD} \ldots\ldots (3.34)$$

The penetration rate usually decreases exponentially with depth:

$$\frac{dD}{dt} = Ke^{-2.303a2D} \ldots\ldots (3.35)$$

The drilling time:

$$t = \frac{1}{2.303a2K}\left(e^{2.303a2D} - 1\right) \ldots (3.36)$$

The time required to change a bit and resume drilling operation (tripping time):

$$tt = \frac{2ts}{ls} D \ldots\ldots (3.37)$$

- Develop the program to compatible with the standard shape, in this Project, MATLAB software, had been used because of it is ability to give a flexible programming and graphic visualization. MATLAB provides an excellent way to keep an eye on the performance of the validation, training and testing data sets. All together which facilitate the optimization process and the sensitivity analysis.

The below figures show the main interface of Drilling Optimization Program (DOP), which consist of four menus:

- File: menu include save, open, and exit.
- Calculation: which include all calculations of :

  2.1 Hydraulic Optimization (Power law & Bingham models).

2.2 Hydraulic Criteria.

2.3 Bit Selection.

2.4 ROP (ROP Models, Operation Condition).

- Help (Contents, about, Contact Us).
- View.


Figure 3.2 Drilling Optimization program (DOP)


Figure 3.3 Starting window: File

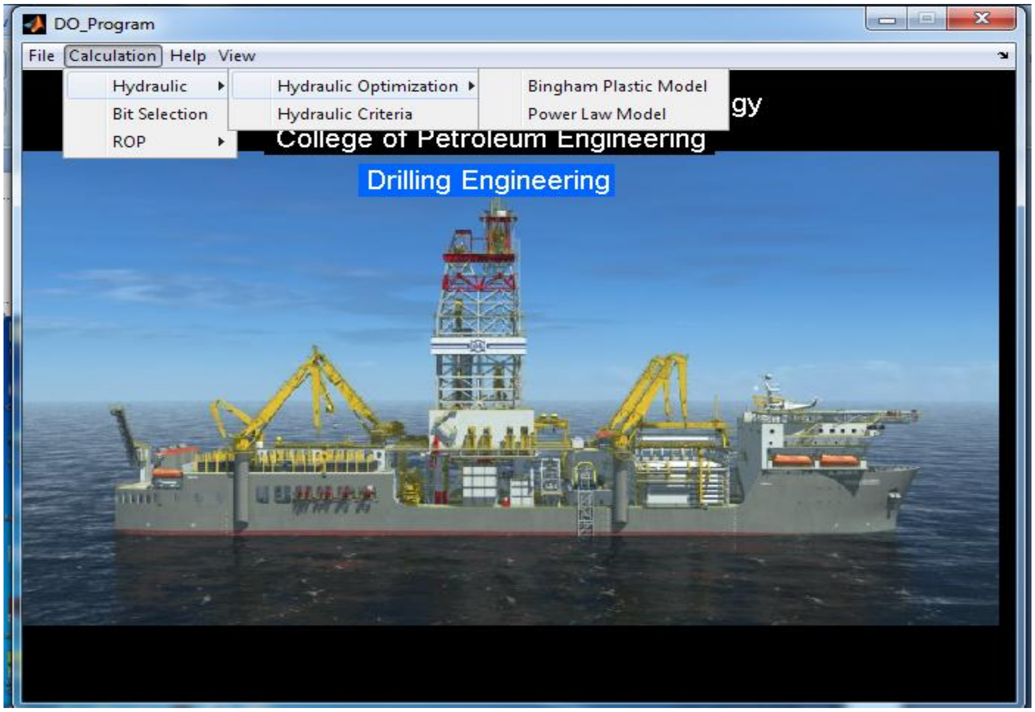


Figure 3.4 Starting window: Calculation (Hydraulic).

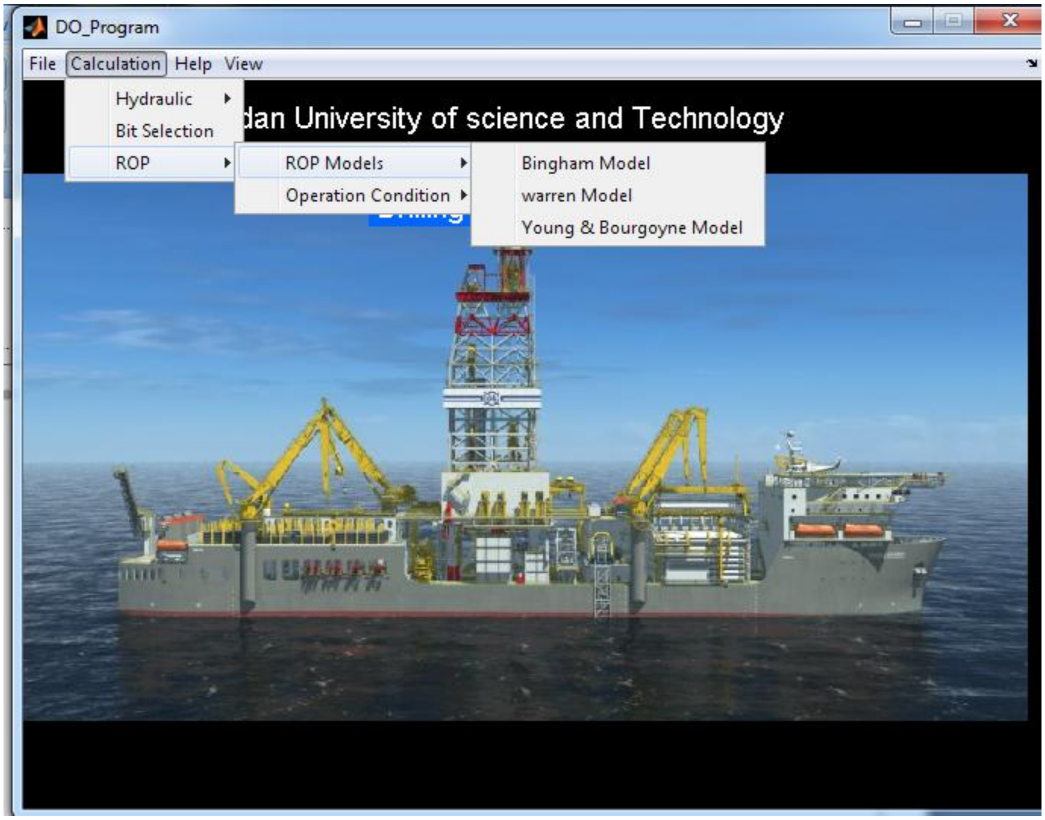


Figure 3.5 Starting window: Calculation (ROP Model)

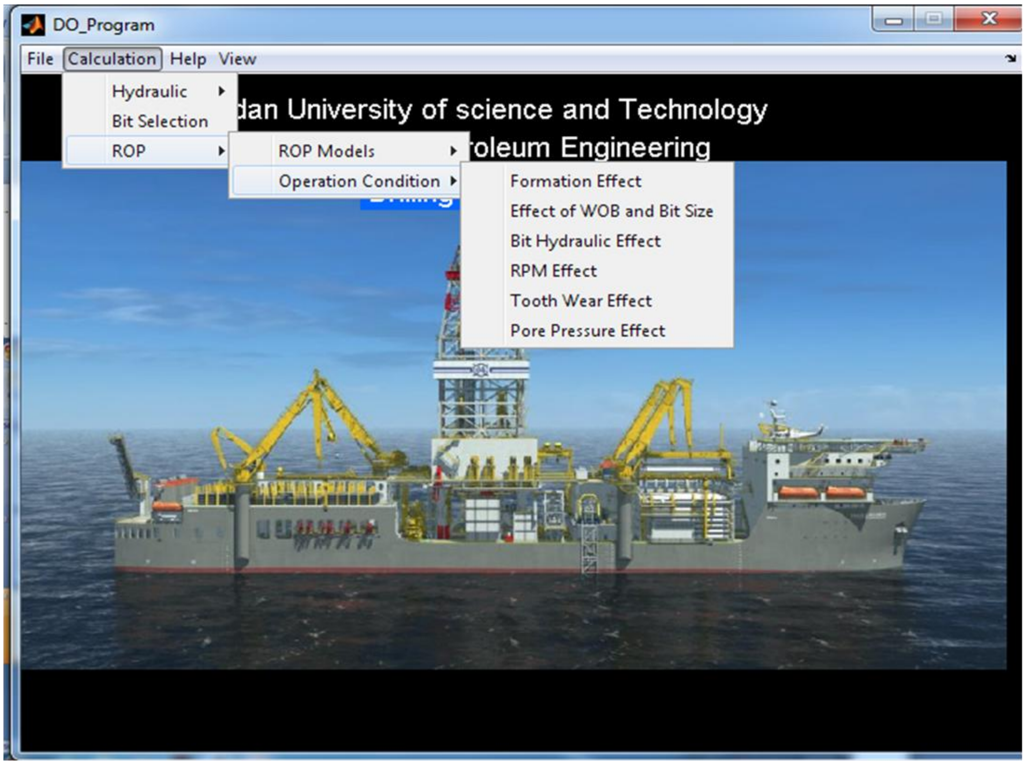


Figure 3.6 Starting window: Calculation (operation conditions)


Figure 3.7 Starting window: Help

## 3.3 Data preparation

- Collect real data that involve desirable parameters which will help in the project form the industry.
- Preparation of the data.
- Apply **GUI.**

## 3.4 Using PAYZONE for verification:

- To check this model is physically correct or not trend analysis should be present **PAYZONE** drilling simulator which is international program was used for verification using same data and compare the results with that we get it from **GUI.**

  **PAYZONE** is a computer program that simulates the drilling of a hydrocarbon or geothermal well. The heart of the program is a drilling mechanics algorithm that calculates the state of wear of a drill bit and its resulting rate of penetration as a function of the type of drill bit, the operating parameters and the nature of the rocks being penetrated.

  **PAYZONE** functions are divided between nine different applications. This section provides a brief overview of each of these applications and explains how they can be used together to create and run simulations.

  Before we start, we have to assemble the information that the simulator needs to operate. It is built up of contributions from six primary editors (litho, drill bits. BHAs, muds. casings and settings), whose output is then combined by the State Editor into a State file. The State file is the data source from which the simulator runs the simulation.
- Discussion and conclusion.

## 3.5 Tools:

The tools used in this project are summarized in the table below:

Table 3.3 Tools and functions

| **Tool** | **Function** |
|---|---|
| Pay zone drilling simulator | Verification |
| GUI at MATLAB software | Modeling and prediction |
| Microsoft Office Word | To write a report |
| Microsoft power point | Prepare presentations |

## 3.6 Gantt charts:

Table 3.4 Semester1

| Discretion | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Topic selection | | | | | | | | | | | | | | | |
| Background study about the project | | | | | | | | | | | | | | | |
| Submission of Extended proposal | | | | | | | | | | | | | | | |
| Literature Research about (ROP&GUI) Proposal defense | | | | | | | | | | | | | | | |

Table 3.5 the vacation

| Discretion | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Apply GUI for hydraulic | | | | | | | |
| Introduction | | | | | | | |
| Apply GUI for drilling optimization | | | | | | | |
| Literature Research about (ROP&GUI) | | | | | | | |

Table 3.6 Semester2

| Discretion | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Methodology | | | | | | | | | | | | | | | |
| Work on the optimization using Drilling simulator And GUI | | | | | | | | | | | | | | | |
| Result And Discussions | | | | | | | | | | | | | | | |
| Conclusion And Recommendation | | | | | | | | | | | | | | | |

# Chapter 4

# Result and Discussion

## 4.1 Review:

The idea of the program was developed due to the uneconomical drilling processes where, companies ‘operations isn’t cost efficient.

A program was developed to calculate to calculate the optimum drilling rate (ROP) whith the lowest cost.

It firstly, estimates the hydraulic parameters then uses the results to estimate the impact force, needed to calculate (ROP) by BYM.

Two more models were used to compare their results with BYM (verification process).

Input into program is made by either, ‘a text file’ which is already prepared, or through ‘direct input ‘of values in table.

The program has input capacity of501parameters.

## 4.2 Bit Selection:

Selecting the proper bits for a well is an important decision that affects the overall well cost. In order to choose the suitable bit on need to study and predict the bit performance, hence many factors must be evaluated such as:

1) Tooth wear.
2) Bearing wear.
3) Bit cost.
4) Expected parameters (weight on bit, rotary speed….etc).
5) Formation types and properties.

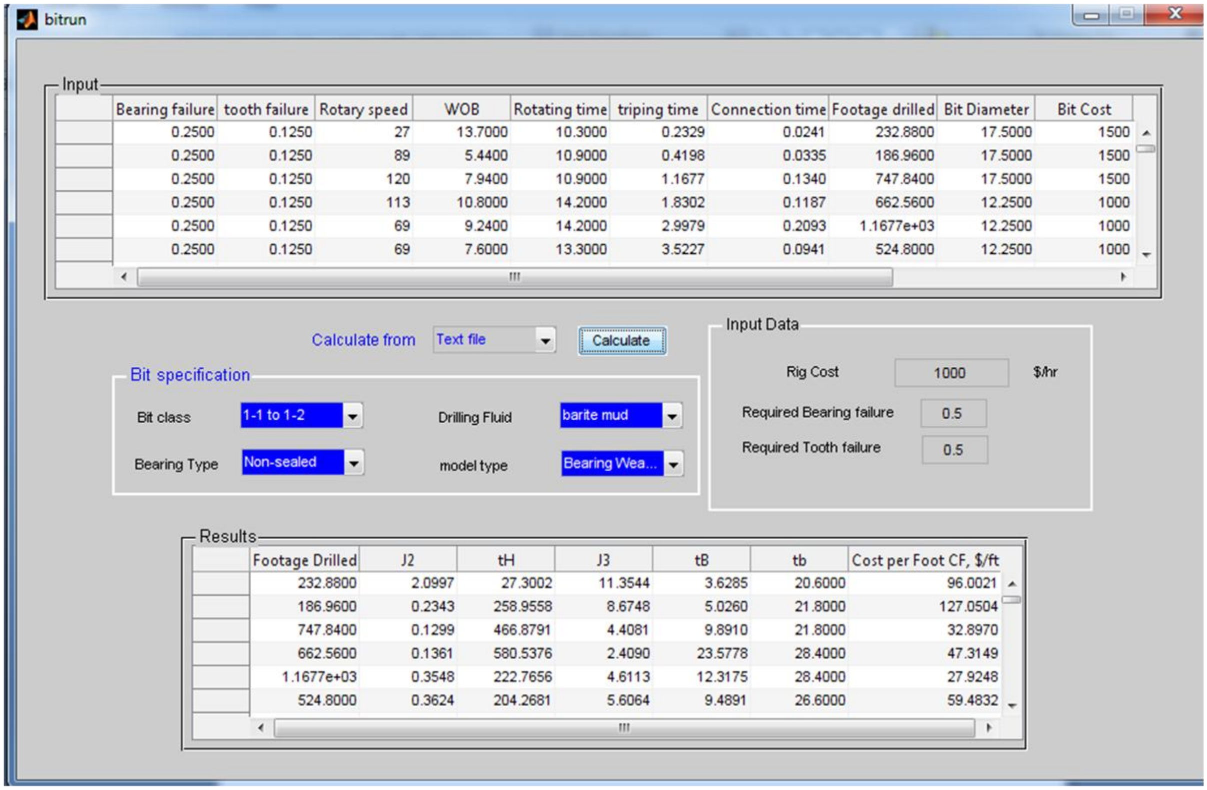


Figure 4.1 Bit selection depending on Bearing wear or tooth wear

### 4.2.1 Tooth wear:

The bit class used in this program include: 1-1 to 1-2, 1-3 to1-4, 2-1 to 2-2, 2-2, 3-1, 3-2, 3-3 and 4-1. According to bit class the values of H1 and H2 are selected to calculate bit bearing.

Table 4.1 Recommended Tooth-Wear Parameters for Rolling-Cutter Bits

| Bit class | H1 | H2 | (W/d)max |
|---|---|---|---|
| 1-1,1-2 | 1.9 | 7 | 7 |
| 1-3,1-4 | 1.84 | 6 | 8 |
| 2-1,2-2 | 1.8 | 5 | 8.5 |
| 2-2 | 1.76 | 4 | 9 |
| 3-1 | 1.7 | 3 | 10 |
| 3-2 | 1.65 | 2 | 10 |

Table 4.2 effect of rotary speed, weight on bit and tooth failure on tooth wear.

| Rotary speed, rpm | Weight on Bit,1000Ib | Tooth failure, h | **Tooth wear, $\tau_H$** |
|---|---|---|---|
| 27 | 13.7 | 0.125 | **27.3002** |
| 89 | 5.44 | 0.125 | **258.9558** |
| 120 | 7.94 | 0.125 | **466.8791** |
| 113 | 10.8 | 0.125 | **426.5376** |
| 69 | 9.24 | 0.125 | **222.7656** |

- Effect of Rotary Speed on tooth wear: the rate of tooth wear increases as the rotary speed increases -non-linear relationship.
- Effect of Bit Weight on Tooth wear: the rate of tooth wear is not stabilized with weight on bit. For example at **WOB=13.7**=> **$\tau_{H=}$ 27.3002, WOB=5.44**=> **$\tau_{H=}$ 258.9558 and WOB=10.8**=> **$\tau_{H\,=}$ 246.5376.**
- Effect of Tooth Wear on Tooth Wear: The rate at which a bit tooth wears decreases as the tooth becomes progressively worn.

### 4.2.2 Bearing wear:

The bit Bearing wear used in this program include: Non-sealed, Sealed roller bearings and sealed journal bearings. According to bearing type the values of B1 and B2 are selected to calculate bit bearing wear.

Table 4.3 Recommended Bearing-Wear Parameters for Rolling-Cutter Bits

| Bearing Type | Drilling Fluid | $B_1$ | $B_2$ |
|---|---|---|---|
| Non-sealed | barite mud | 1 | 1 |
| - | sulfide mud | 1 | 1 |
| - | water | 1 | 1.2 |
| Sealed roller bearings | clay/water mud | 1 | 1.5 |
| Sealed journal bearings | - | 0.7 | 2 |

Table 4.4 effect of rotary speed, weight on bit and tooth failure on Bearing wear.

| Rotary speed, rpm | Weight on Bit,1000Ib | bearing failure, h | **Bearing wear, $\tau_b$** |
|---|---|---|---|
| 89 | 5.44 | 0.25 | **20.6** |
| 120 | 7.94 | 0.25 | **21.8** |
| 113 | 10.8 | 0.25 | **21.8** |
| 69 | 9.24 | 0.25 | **28.4** |

- Effect of Bit Weight on Bearing Life: The rate of bearing wear increases rapidly with increases in bit weight.
- Effect of Rotary Speed on Bearing Life: the rate of bearing wear increases directly as the rotary speed increases.

The selection of suitable model depends on abrasiveness factor (Af):

Af= 1 ~ 4, use bearing wear mode.
Af = 6 ~ 10, use tooth wear mode.
Af = 4 ~ 6, try both types to see which gives the minimum cost.

### 4.2.3 Bit cost:

Table 4.5 drilling cost analysis

| Depth, ft | **Cost per foot, $/ft** |
|---|---|
| 232.88 | **96.0021** |
| 419.84 | **223.0525** |
| 1167.68 | **255.9495** |
| 1830.24 | **303.2644** |
| 2997.94 | **331.1829** |

Cost-per-foot studies are useful in defining optimum, minimum-cost drilling conditions.

The cost of the footage drilled during a single bit run is the sum of three costs: bit costs, trip costs, and rig operating costs for the time required to drill the footage. If the bit run cost is divided by the footage drilled, the result is the cost per foot for the interval drilled. The cost of the bit and the cost to trip the bit are fixed for a particular bit run.

#### 4.2.3.1 Drilling cost vs. depth curve:

From figure (4.2) we notice that the drilling cost is increased with depth until 6000ft approximately after that it became constant that is because of bit failure (tooth wear or bearing wear) there is no significant change in depth, may be this is the time to change the bit at this depth.

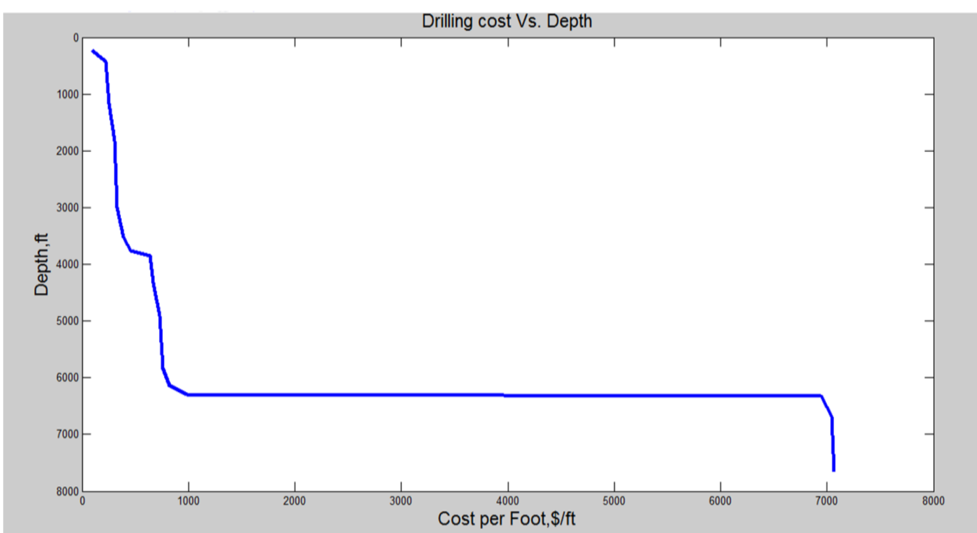


Figure 4.2 Drilling cost vs. depth

# 4.3 Optimization of Hydraulics:

## 4.3.1 Hydraulics Models:

There are two types of hydraulic models:

1. Bingham Plastic model
2. Power law model

Decide which model to use, Bingham Plastic or Power Law depend on the fluid type and it's behavior as show in figure (4.3) below:

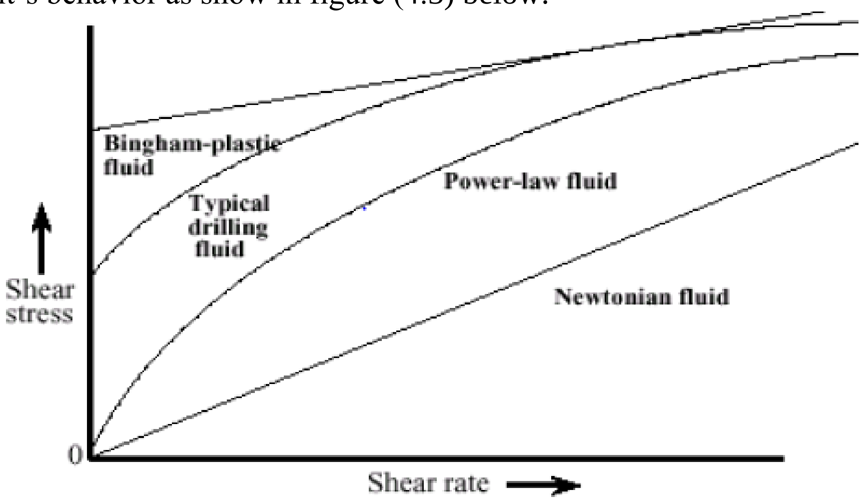


Figure 4.3 Rheological model.

We use both models to determine the hydraulic parameters; the important parameters are circulation losses and nozzle size which are calculated from DOP and introduced in the following table (4.6) from real field data:

Table 4.6 Sample of data for Bingham and Power law models for a real field data

| Depth, ft | Circulation Losses, psi | | Bit Nozzles sizes, in | |
|---|---|---|---|---|
| | Bingham | Power law | Bingham | Power law |
| 232.88 | 301.9424 | 299.3876 | 23.9262 | 23.8175 |
| 419.84 | 374.5327 | 370.0816 | 22.5274 | 22.4115 |
| 1167.7 | 911.1860 | 897.8258 | **19.0681** | **18.9991** |
| 1830.2 | 993.9147 | 967.8448 | 19.9027 | 19.7272 |

Power Law model is mathematically more complex than the Bingham Plastic model but produces greater accuracy than Bingham Plastic model especially in the determination of shear stresses which has great effect in the value of Pressure losses (Circulation losses).

From the table (4.6) above we found a **little** difference in the calculation, for example for depth of 419.84 ft the bit nozzles sizes from Bingham Plastic model (**19.0681**) will be **2*19+1*20** which meaning **two** nozzle with **19 inch** and **one** nozzles with **20 inch,** when the bit nozzles sizes from Power law model (**18.9991**) will be **1*18+2*19** which meaning **one** nozzles with **18 inch** and **two** nozzle with **19 inch.**

The table (4.7) and figures (4.4) & (4.5) below showed the inputs and outputs of the DOP for case study of real field data for the two models Bingham Plastic model and Power law model:

Table 4.7 sample required data, obtained from wells daily drilling progress report

| depth, m | depth, ft | ROP, m/hr. | ROP, ft/hr. | WOB, ton | WOB, 1000Ib | RPM, rpm | SPP, psi | FIOW, gpm | YP,pa |
|---|---|---|---|---|---|---|---|---|---|
| 71 | 232.88 | 7.71 | 25.2888 | 6.9 | 13.7 | 27 | 441 | 549 | 23 |
| 128 | 419.84 | 10.83 | 35.5224 | 2.7 | 5.44 | 89 | 588 | 603 | 23 |
| 356 | 1167.68 | 10.11 | 33.1608 | 4.0 | 7.94 | 120 | 1825 | 874 | 27 |

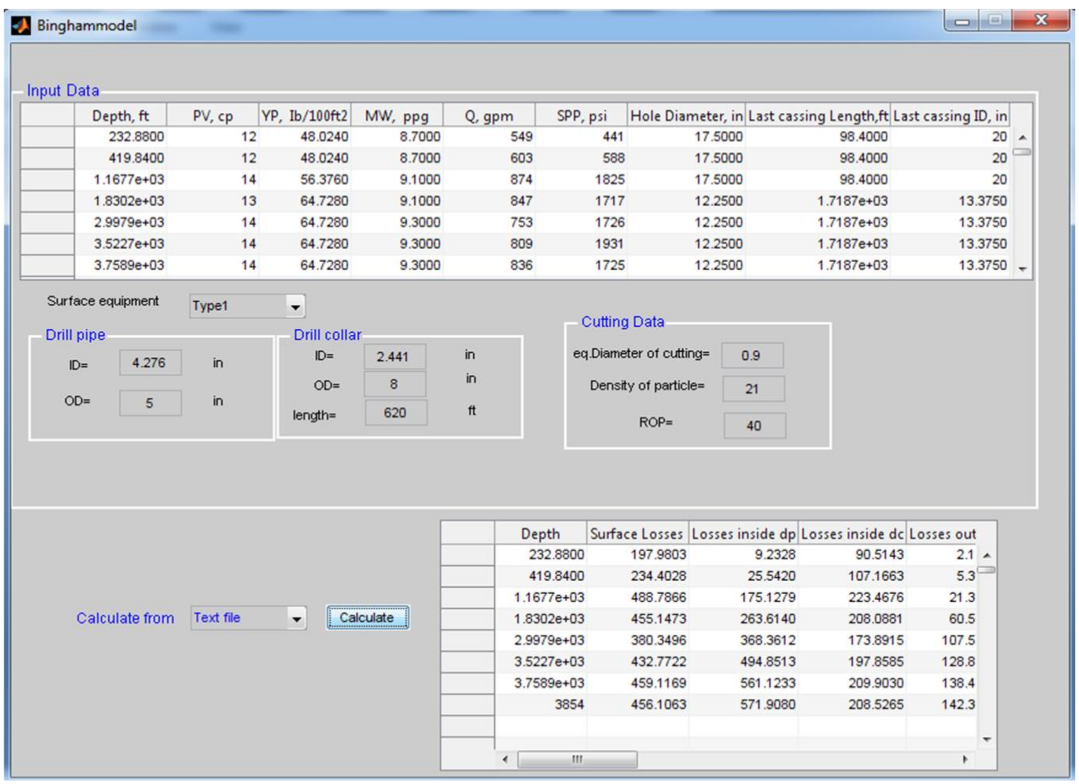


Figure 4.4 Hydraulic Optimization: Bingham Plastic model

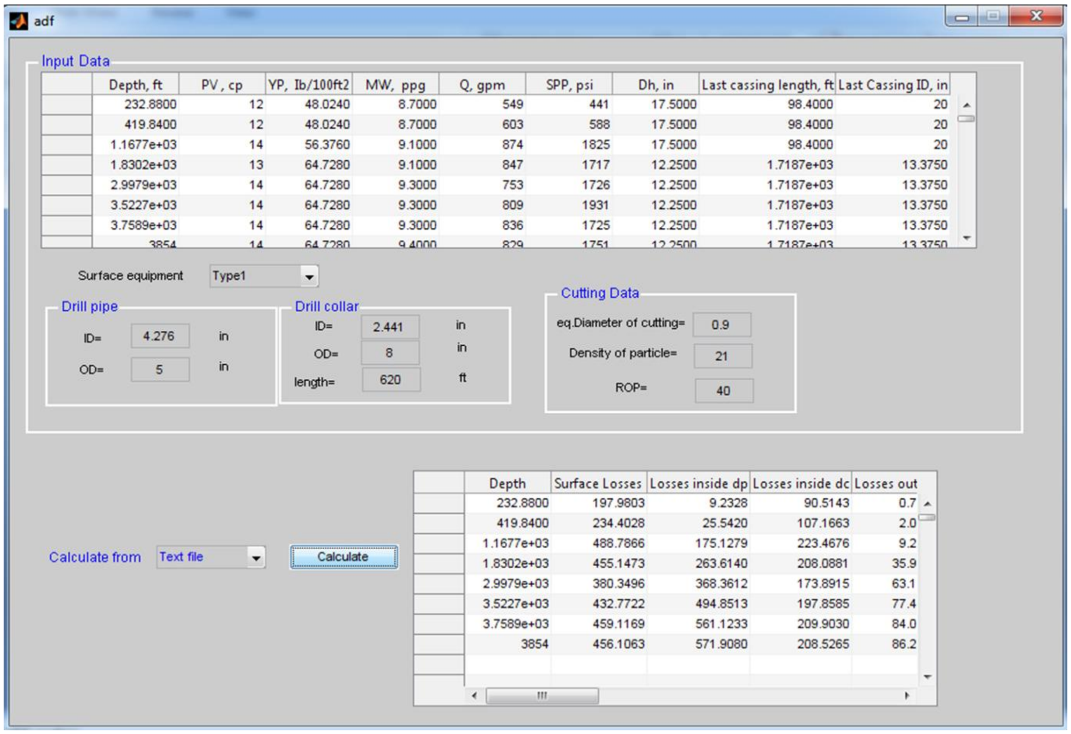


Figure 4.5 Hydraulic Optimization: Power law model.

## 4.3.2 Hydraulic Criteria:

### 4.3.2.1 Design of optimum Flow rates and Bit Nozzles sizes:

The designed optimum flow rates and bit nozzles provide a guideline to preparation of drilling operations. Actual flow rates and bit nozzles can be optimized using field data during drilling operations.

the following are the criteria exist for optimizing bit hydraulics: The maximum hydraulic horsepower criterion (BHHP)

1. The maximum jet impact force criterion (IF), and
2. The maximum nozzle velocity criterion.

We used the first (BHHP) and second (IF) methods to determine optimum flow rates and bit nozzles sizes using a real field data with DOP as shown in the next table (4.8):

Table 4.8 Sample of data (q & dn) for BHHP and IF methods for a real field data

| Depth, ft | Optimum Flow rates, gpm | | Bit Nozzles sizes, in | |
|---|---|---|---|---|
| | BHHP | IF | BHHP | IF |
| 232.88 | 383.1408 | 468.8276 | 16.5722 | 19.6927 |
| 419.84 | 441.9349 | 540.7706 | 16.5632 | 19.6821 |
| 1167.7 | 775.2697 | 948.6534 | **16.7148** | **19.8622** |
| 1830.2 | 752.1528 | 920.3666 | 16.7167 | 19.8645 |
| 2997.9 | 754.1067 | 922.7574 | 16.8077 | 19.9725 |

The drilling fluid flow rates and bit nozzle sizes should be designed for different depths based on:

- available pump power
- the maximum pump working pressure
- selected criterion for hydraulics optimization
- selected hydraulics model for a given fluid type

From a practical standpoint it is usually convenient to select a pump liner size that will be suitable for the entire well rather than periodically reducing the liner size as the well depth increases to achieve the theoretical maximum.

However, the flow rate should never be reduced below the minimum flow rate required to lift the cuttings in the largest annulus. Larger nozzles have to be used in the subsequent depth to maintain pump pressure less than the maximum pressure (Pressure required to fracture the formation).

We can use the data from the above table (4.8) to select the pump and its liner size which will give an optimum flow rate close as possible to theoretical in the table (4.8) above.

If we made a comparison between the two methods BHHP and IF from table (4.8) above we will found a difference in values between the two methods especially in the values of bit nozzles sizes, for example for depth of 419.84 ft the bit nozzles sizes from BBHP method (**16.7148**) will be **1*16+2*17** which meaning **one** nozzle with **16 inch** and **two** nozzles with **17 inch,** when the bit nozzles sizes from IF method (**19.8622**) will be **1*19+2*20** which meaning **one** nozzles with **19 inch** and **two** nozzle with **20 inch.**

Also when we compare them with hydraulic models Bingham Plastic model and Power law model in table(4.6) we found that the values of bit nozzles sizes from IF is close to the values of it from hydraulic models more than BHHP method.

### 4.3.2.2 Horse Power and Impact Force:

Other important parameters is horse power and impact force which estimated from the two methods BHHP and IF as shown in the next table using DOP for a real field data:

Table 4.9 Sample of data (HP & IF) for BHHP and IF methods for a real field data

| Depth, ft | Horse Power, hp | | Impact Force, Ibf | |
|---|---|---|---|---|
| | BHHP | IF | BHHP | IF |
| 232.88 | 65.8846 | 60.5405 | 334.5094 | 354.7044 |
| 419.84 | 101.3265 | 93.1075 | 445.5307 | 472.4282 |
| 1167.7 | 551.6999 | 506.9494 | 1408.2 | 1493.3 |
| 1830.2 | 503.5743 | 462.7274 | 1325.2 | 1405.2 |
| 2997.9 | 507.5289 | 466.3613 | 1346.7 | 1428.0 |

The significant difference is that the values of horse power from BHHP method is larger than the values of it from the IF method, also the values of impact force from IF method is larger than the values of it from BHHP method, as shown in the table (4.9) above. Therefore, we take the values of horse power from BHHP method and the values of impact force from IF method.

The figures (4.6) below showed the inputs and outputs of the DOP for case study of real field data for the two methods BHHP and IF:

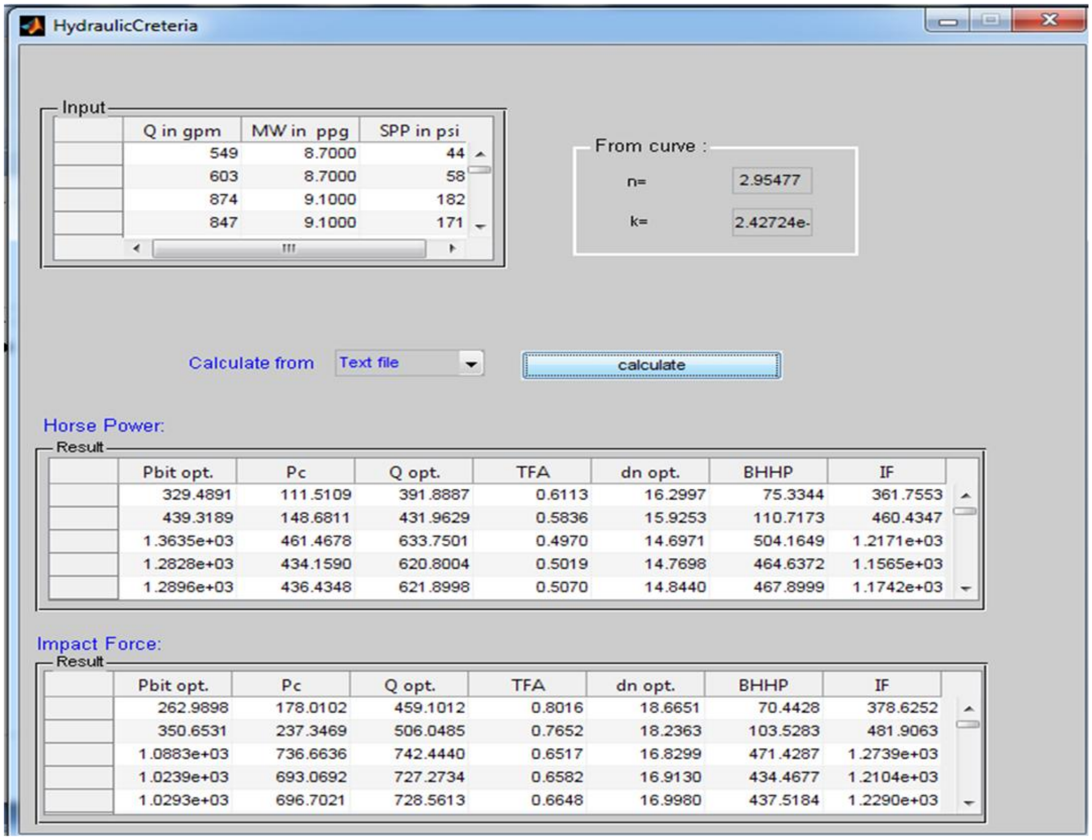


Figure 4.6 Hydraulic Optimization: Hydraulic Criteria.

### 4.3.2.3 Determination of Power Law Index (n) and Consistency Index (k):

For all of the previous calculation we need to found Power Law Index (n) and Consistency Index (k) from the curve of pump flow rate versus circulation pressure as shown the figure (4.7) below:

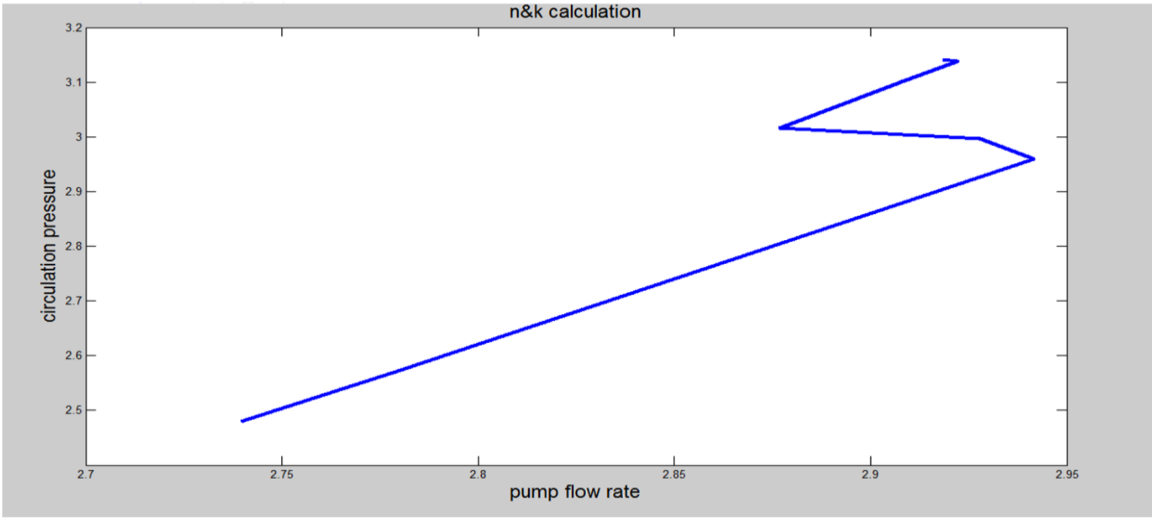


Figure 4.7 pump flow rate vs. circulation pressure.

n is the value of the slope of the straight line in the figure(4.7) above, and K calculated from equation in table (3.2)

We found that the values of **n** and **K** is **2.01514** and **0.000910525** consequently as shown in figure (4.6) .

## 4.4 Optimization of ROP:

There are three important models to optimize ROP in oil industry: Bingham Model, Warren Model and Bourgoyne Young Model.

### 4.4.1 Bingham Model:

Simple model usually less reliability because neglecting important factor which is the depth. Figure (4.8) show that ROP increase with increase of rotary speed up to 100 rpm, after that the ROP decrease because of bit wear.

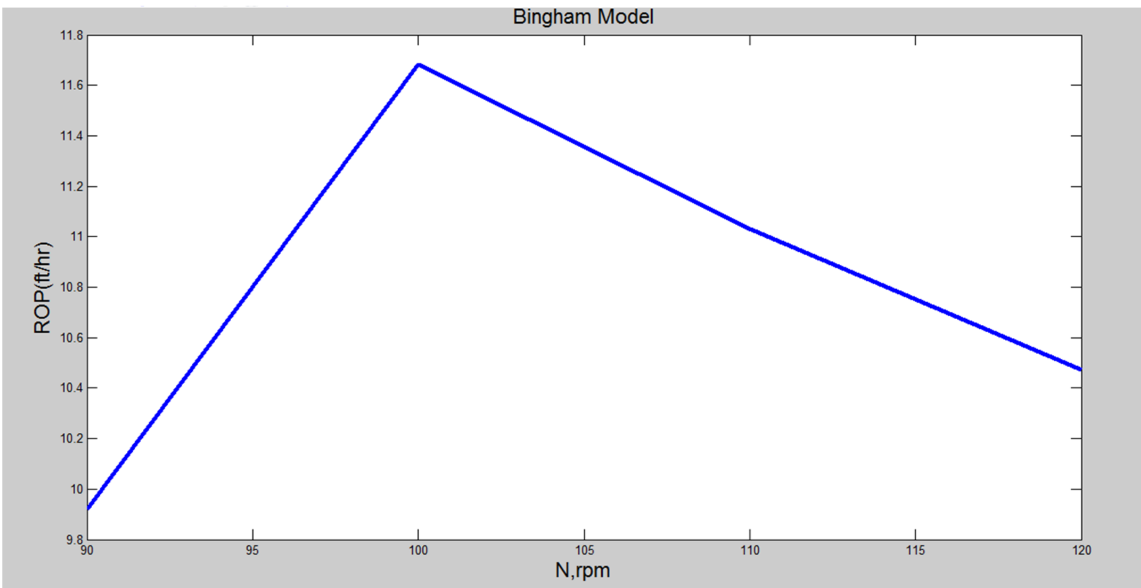

Figure 4.8 ROP vs. RPM (from Bingham model)

Also from Figure (4.9) ROP increase with WOB but not proportionally ,ROP increase with WOB up to specific value after that it tends to decrease ,that may be due to bit crushing or tooth wear …

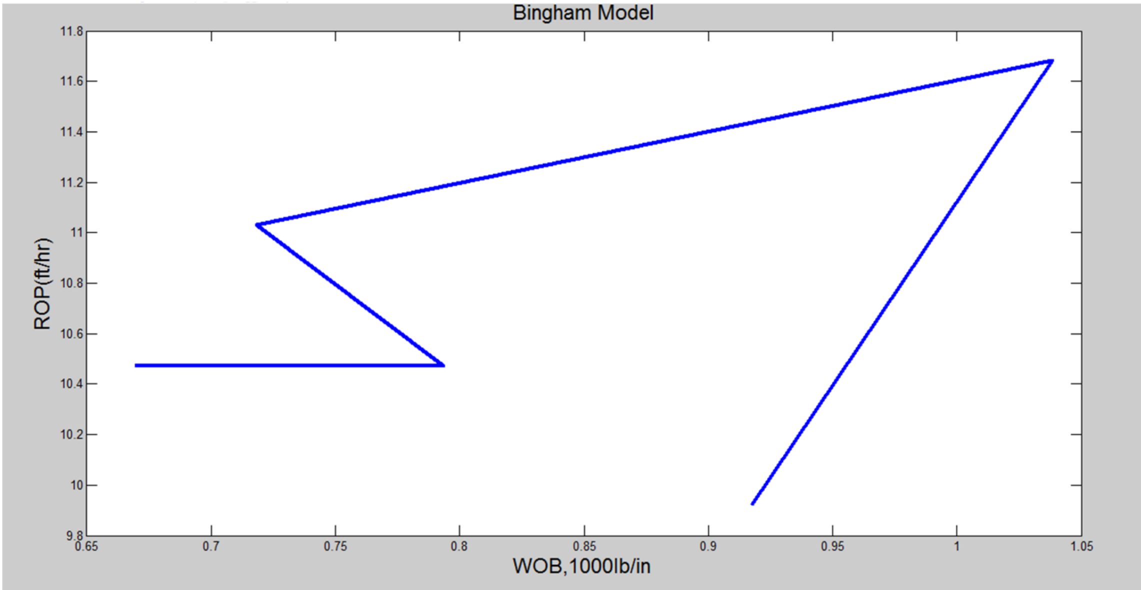


Figure 4.9 ROP vs. WOB (from Bingham model)

### 4.4.2 Warren Model:

He proposed that ROP can be controlled by cutting removal process, cutting generation process or combination of both.

Figure (4.10) show that ROP increase with N directly. At 98 rpm ROP decrease that may be due to formation effect. As we see from table (4.10) this model is very poor in predicting ROP.

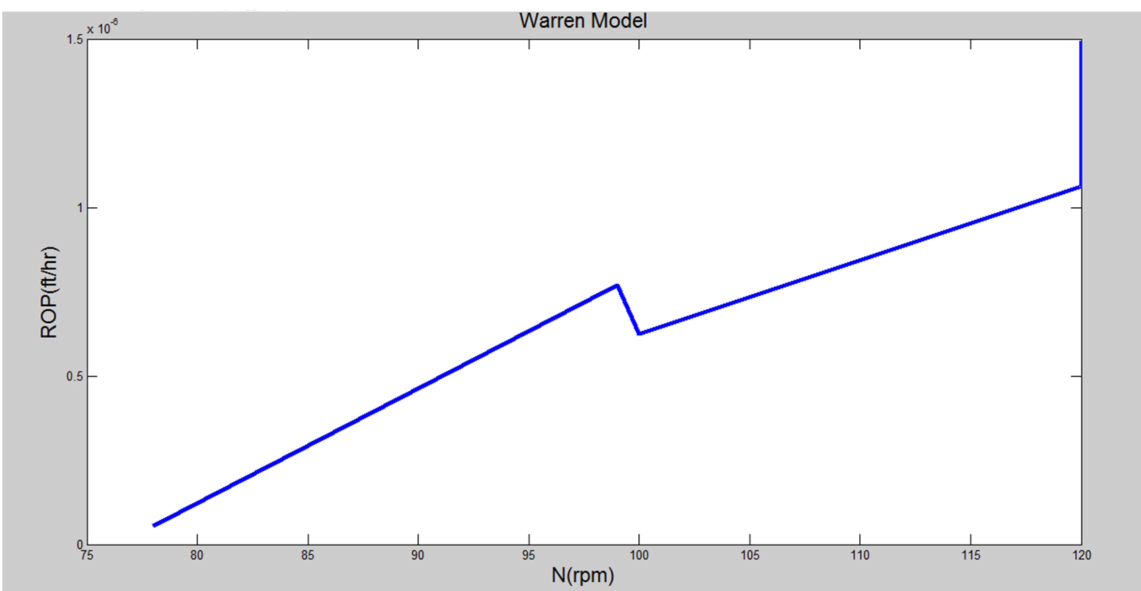


Figure 4.10 ROP vs. RPM (from Warren model)

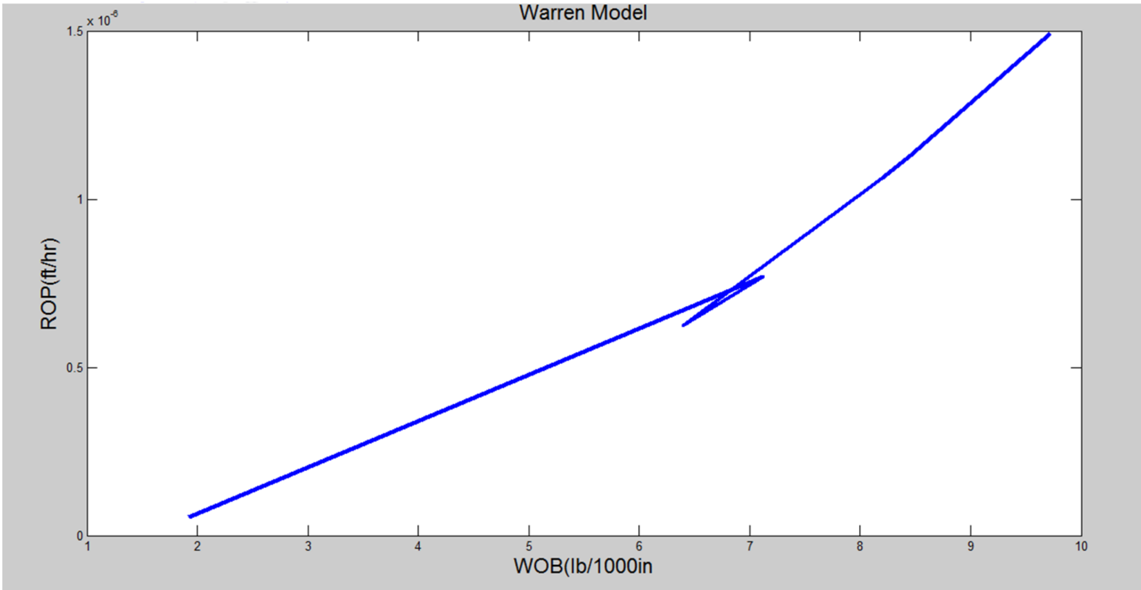


Figure 4.11 ROP vs. WOB (from Warren model)

In this model ROP increase with WOB proportionally.

## 4.4.3 Bourgoyne and Young Model:

Bourgoyne and Young employ multiple regression method to determine unknown coefficients. But, this scheme provides results out of recommended bounds in some situations. To be more precise, multiple regression method may result in negative or zero values. It is taken for granted that negative or zero values for coefficients are physically meaningless. Penetration rate or a zero value implies that increasing the weight on bit has no effect on the drilling rate .figure (4.12) show predict ROP with depth .

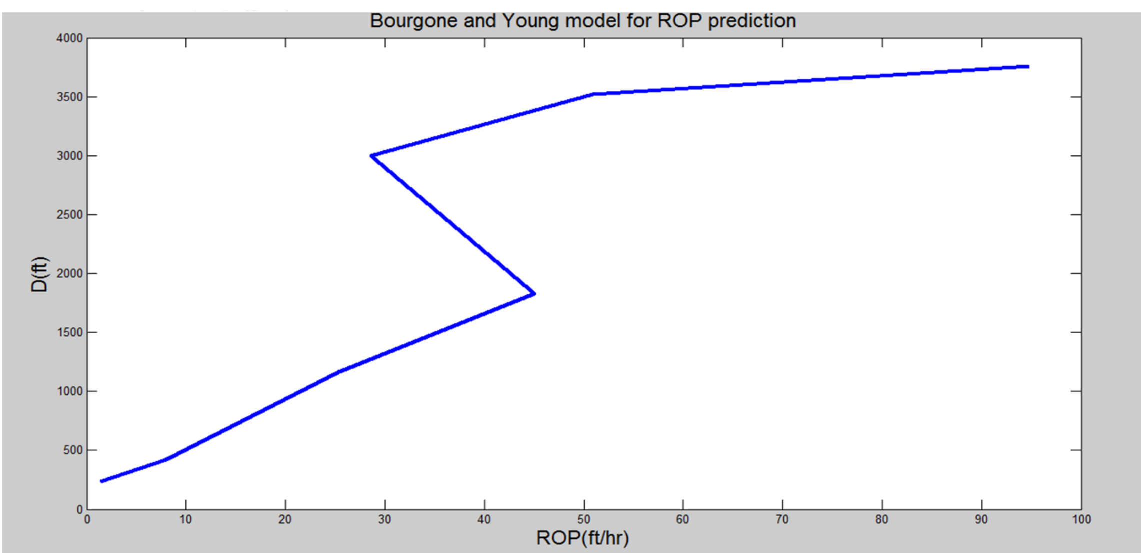


Figure 4.12 ROP vs. Depth (from Bourgoyne and Young model)

### 4.4.4 Comparison between ROP models:

The table (4.10) below show actual values of ROP and values of ROP Models which calculated from the program. We can see that the Bourgoyne & Young model usually give a bigger ROP values than others.

Table 4.10 the result of Analysis for Field Data

| Hole size(in) | Depth (ft) | ROP (ft/hrs.) (actual) | ROP (ft/hrs.) (Bingham) | ROP (ft/hrs.) (Warren) | ROP (ft/hrs.) (Bourgoyne & Young) |
|---|---|---|---|---|---|
| 17.5 | | 25.2888 | 31.9619 | 7.5431E-07 | 1.2829 |
| | | 35.5224 | 15.6284 | 1.5098E-07 | 7.8050 |
| | | 33.1608 | 13.0629 | 3.4144E-07 | 29.7859 |
| 12.25 | | 33.1608 | 10.8558 | 1.8197E-07 | 52.2804 |
| | | 35.5224 | 14.5948 | 1.2069E-07 | 33.2064 |
| | | 58.6464 | 14.5948 | 8.1646E-07 | 60.1814 |
| | | 107.19 | 13.5598 | 5.3402E-07 | 110.2329 |
| | | 57.3344 | 11.7524 | 7.7024E-07 | 76.1228 |
| | | 47.6912 | 11.6818 | 6.2359E-07 | 67.0914 |
| | | 54.2512 | 10.4713 | 1.0617E-06 | 104.5678 |
| | | 52.4472 | 10.4713 | 1.1301E-06 | 117.5370 |
| | | 34.276 | 10.4713 | 1.4918E-06 | 89.2896 |
| | | 24.7312 | 11.0325 | 1.2017E-06 | 62.5457 |
| | | 12.1688 | 11.6818 | 2.4633E-06 | 28.5742 |
| 8.5 | | 38.8024 | 9.9211 | 2.7147E-06 | 87.2593 |
| | | 38.8024 | 9.9211 | 2.7147E-06 | 84.8838 |

The graphical representation of tables (4.10) are presented in Figure (4.13) for PDC and roller cone bits, respectively. As seen from figures, it can be concluded that the Bourgoyne & Young model can estimate rate of penetration with a reasonable accuracy. Figure indicate that Bourgoyne & Young model is more accurate than Bingham model, which is more accurate than warren model.

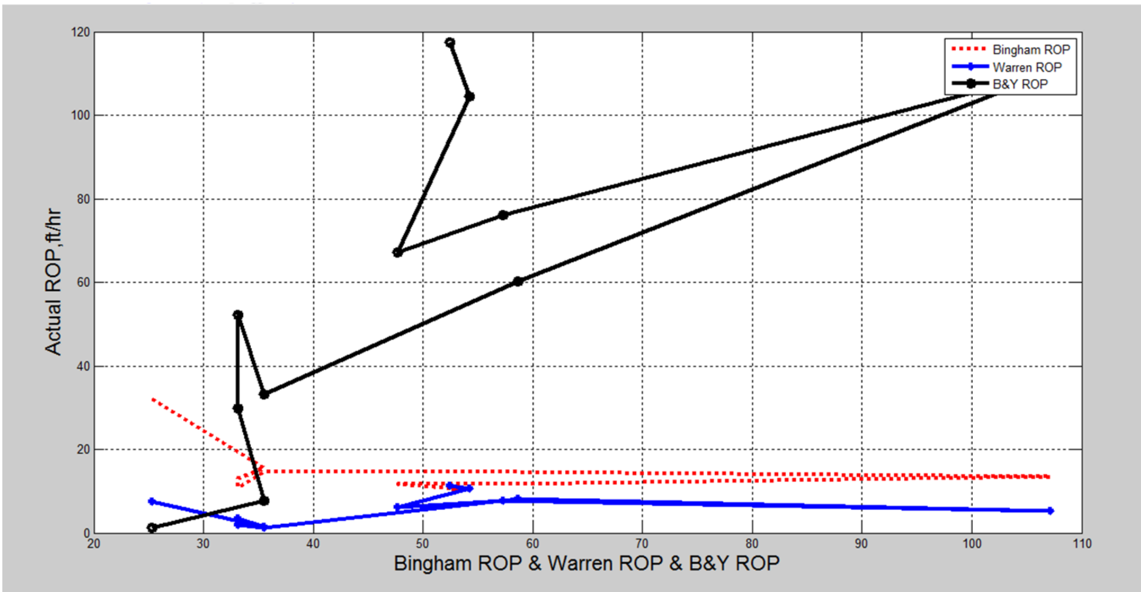


Figure 4.13 actual ROP versus calculated ROP

The table (4.11) Show the Statistical Parameters of all three models, Bingham, Warren and BYD model. From the Statistical values; observed Bourgoyne &Young model is more accuracy than Bingham model , it's more accuracy than warren model, because the Bourgoyne &Young model depend on many factors such as formation pressure, tooth wear &coefficient values….etc.

Table 4.11 statistical Parameters for Models

| Hole size(in) | ROP Models | Average absolute error% | Correlation Factor($R^2$) |
|---|---|---|---|
| 17.5 | Bingham | 47.663 | 0.869 |
| | Warren | 99.999 | 0.130 |
| | Bourgoyne | 41.0436 | 0.940 |
| 12.25 | Bingham | 59.779 | 0.843 |
| | Warren | 99.998 | 0.790 |
| | Bourgoyne | 73.467 | 0.960 |
| 8.5 | Bingham | 74.431 | 0.607 |
| | Warren | 99.999 | 0.600 |
| | Bourgoyne | 40.646 | 0.870 |

## 4.5 Software Verification using PAYZONE:

The DOP is compared with Payzone (Drilling Simulator Software) an investigate the accuracy and reliability of it. An analysis of the plots in the offset area surrounding the prospect well can provide the following information:

a) Expected drilling times for various intervals.
b) Identification of better drilling conditions by examining the lowest drilling times in the offset wells.
c) Location of potential problem zones by comparing common difficulties in the wells.

After the offset wells have been analyzed, a projected depth versus days plot is prepared for the prospect well.

The drilling time can be estimated based on experience and historical penetration rates. Note that the penetration rate depends on: type of bit used, wear of bit used, drilling parameters applied (WOB, RPM), hydraulics applied (hydraulic impact force due to mud flow through nozzles), effectiveness of cuttings removal, formation strength and formation type. Therefore an analytic prediction of the rate of penetration (ROP) is impossible. Estimations are generally based on the assumption of similar parameters and historic ROPs.

Figure 4.14 shows an acceptable match between DOP and Payzone.

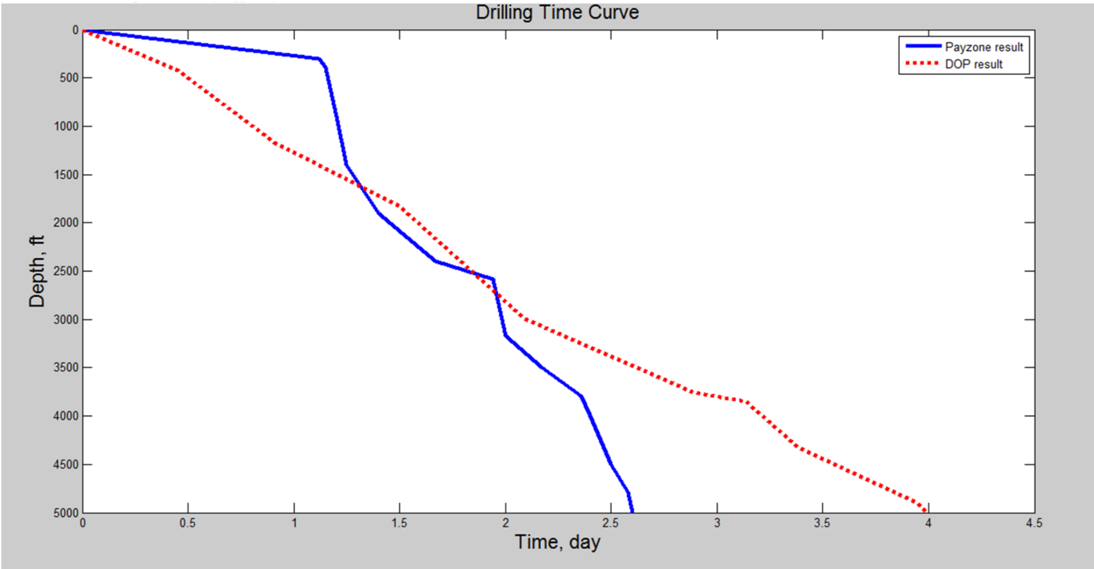


Figure 4.14 drilling time curve for **PAYZONE** drilling simulator versus **DOP**

# 4.6 Summary:

## 4.6.1 Input to a Program (DOP):

Table 4.12 Input to a Program (DOP):

| | | | | | |
|---|---|---|---|---|---|
| Depth(ft) | PV(cp) | YP(Ib/100ft2) | MW(ppg) | Q(gpm) | SPP(psi) |
| Dh(in) | Last casing length | Last casing diameter | Drillpipe data | Drillcollar data | Bearing failure |
| tooth failure | WOB(1000Ib) | RPM(rpm) | Footage drilled(ft) | Bit cost($) | Bit class |
| Drilling fluid | Bit bearing model | e(Bingham constant) | k(Bingham constant) | a5(Bingham constant) | S(warren) |
| a(warren constant) | c(warren constant) | b(warren constant) | gp(ppg) | ECD(ppg) | - |

## 4.6.2 Parameter Values Given by a Computer Program:

- J1
- J2
- Af

### 4.6.3 Data Given by a Computer Program:

Table 4.13 Data Given by a Computer Program

| | | | | |
|---|---|---|---|---|
| Surface loss(psi) | Loss in side drill pipe | Loss around drill pipe(psi) | Loss in side drill collar(psi) | Loss around drill collar(psi) |
| Pbit(from power law or Bingham) | Nozzle velocity(in$^2$/s) | TFA(in$^2$) | Nozzle size(in) | $P_C$ (psi) |
| Pbit(from IF or BHHP) (psi) | Q.opt (from IF or BHHP) (gpm) | TFA (from IF or BHHP) (in$^2$) | dn.opt (from IF or BHHP) | BHHP(HP) |
| IF(Ibf) | Cost per foot($/ft) | $\tau_H$ | $\tau_B$ | ROP(from Bingham model)(ft/hr) |
| ROP(from Warren model)(ft/hr) | ROP(from B&Y model)(ft/hr) | - | - | - |

# CHAPTER 5

# Conclusions and Recommendations

## 5.1 Conclusions:

According to the field data, there are several method to reduce the drilling cost of future wels.one of these methods is the optimization of drilling parameters to obtain the maximum rate of penetration (ROP) in each bit run. Many parameters affect ROP like hoe cleaning (including drill string rotation speed (N), weight on bit (WOB) tooth wear and formation hardness.

- ROP is optimized by using the **DOP** (Drilling Optimization Program) and used to predict future performance of X well at 7345.8 ft.
- The correctness of the results were ensure from references results and PAY ZONE drilling simulator as shown in figure (4.14).
- Selecting the proper bits for a well is an important decision that affects the overall well cost. In order to choose the suitable bit on need to study and predict the bit performance, hence many factors must be evaluated such as:
    1) Tooth wear.
    2) Bearing wear.
    3) Bit cost.
- We used (BHHP) and (IF) methods to determine optimum flow rates and bit nozzles sizes using a real field data with DOP as shown in the table (4.8).
- It can be concluded that the Bourgoyne & Young model can estimate rate of penetration with a reasonable accuracy than Bingham model, which is more accurate than warren model.

- Increasing WOB or rotary speed does not always increase ROP. This study shows in some parts which the drier exerts high WOB and N, the ROP value decrease due to cleaning problem and bit floundering.

## 5.2 Recommendations:

DOP can be used to optimize the drilling parameters which will lead to reduce the cost of the drilling. All researchers and developers should be work on Graphical User Interface (GUI) to improve the code as well as the prediction process, because it will improve the accuracy of DOP.

The results of program can be used as data for any screening program to choose optimum operation conditions for a given field.

The program needs more data to affirm that its results are more accurate.

The program needs Additional data when it use for horizontal wells.

The program can be developed by adding optional formation type window for user to select the proper mud type.

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# APPENDEX:

## Programming Code:

### Hydraulic Criteria:

```
Pc(i)=P1(i)+P2(i)+P3(i)+P4(i)+P5(i)+P6(i);
Vn(i)=33.36*(Pb(i)/m(i))^0.5;
A(i)=0.32*Q(i)/Vn(i);
dn(i)=32*(4*A(i)/(3*pi))^0.5;
p4(i)=P5(i)+P6(i);
p5(i)=P4(i);
end
se=[L';P1;P2;P3;p4;p5;Pc;Pb;Vn;A;dn;Vt1;Vt2;Ca1;Ca2]';
set(handles.bbb,'data',se);

function pushbutton1_Callback(hObject, eventdata, handles)
fg=get(handles.tf,'value');
switch fg
    case 1
        [a,b]=uigetfile('*.txt');
        ar=textread(fullfile(b,a));
    case 2
        ar=str2double(get(handles.f,'data'));
end
Qprev=ar(:,1);
Ps=ar(:,3);
M=ar(:,2);
for i=1:length(M)
    if isnan(M(i))==1
        M(i)=0;
        Ps(i)=0;
        Qprev(i)=0;
    end
end
M=M(M>0);
Ps=Ps(Ps>0);
Qprev=Qprev(Qprev>0);
switch fg
    case 1
        so=[Qprev,M,Ps];
        set(handles.f,'data',so);
end
H=guidata(Binghammodel);
v=get(H.se1,'data');
Pcprev=v(:,7);
for i=1:length(Pcprev)
    if isnan(Pcprev(i))==1
```

```
        Pcprev(i)=0;
    end
end
Pcprev=Pcprev(Pcprev>0);
fg=get(handles.tf,'value');
figure
plot(log10(Qprev),log10(Pcprev),'linewidth',3)
title('n&k calculation','fontsize',16)
xlabel('pump flow rate','fontsize',16)
ylabel('circulation pressure','fontsize',16)
y=polyfit(Qprev,Pcprev,1);
N=y(1);
for i=1:length(M)
    K1=Pcprev(1)/(Qprev(1))^N;
end
set(handles.nn,'string',N);
set(handles.kk,'string',K1);
for i=1:length(M)
Pbo(i)=(N/(N+1))*Ps(i);
Pc(i)=Ps(i)-Pbo(i);
Qopt(i)=(Pc(i)/K1)^(1/N);
BHHP1(i)=Pbo(i)*Qopt(i)/1714;
IF1(i)=Qopt(i)*sqrt(M(i)*Pbo(i))/58;
tfa(i)=0.0096*Qopt(i)*sqrt(M(i)/Pbo(i));
dno(i)=32*sqrt(4*tfa(i)/(3*pi));
Pbof(i)=(N/(N+2))*Ps(i);
Pcf(i)=Ps(i)-Pbof(i);
Qoptf(i)=(Pcf(i)/K1)^(1/N);
BHHP2(i)=Pbof(i)*Qoptf(i)/1714;
IF2(i)=Qoptf(i)*sqrt(M(i)*Pbof(i))/58;
tfaf(i)=0.0096*Qoptf(i)*sqrt(M(i)/Pbof(i));
dnof(i)=32*sqrt(4*tfaf(i)/(3*pi));
end
hpp=[Pbo;Pc;Qopt;tfa;dno;BHHP1;IF1]';
iff=[Pbof;Pcf;Qoptf;tfaf;dnof;BHHP2;IF2]';
set(handles.mhp,'data',hpp);
set(handles.mif,'data',iff);
```

**Bit Selection:**

```
function pushbutton1_Callback(hObject, eventdata, handles)
% hObject    handle to pushbutton1 (see GCBO)
% eventdata  reserved - to be defined in a future version
of MATLAB
% handles    structure with handles and user data (see
GUIDATA)
fg=get(handles.aca,'value');
switch fg
```

```
    case 1
        [a,b]=uigetfile('*.txt');
        ar=textread(fullfile(b,a));
    case 2
        ar=str2double(get(handles.run,'data'));
end
bf=ar(:,1);
hf=ar(:,2);
N=ar(:,3);
W=ar(:,4);
tbp=ar(:,5);
tt=ar(:,6);
tc=ar(:,7);
D=ar(:,8);
db=ar(:,9);
cb=ar(:,10);
cr=str2double(get(handles.rc,'string'));
bfn=str2double(get(handles.b,'string'));
hfn=str2double(get(handles.t,'string'));
for i=1:length(N)
    if isnan(N(i))==1
        N(i)=0;
        bf(i)=0;
        hf(i)=0;
        W(i)=0;
        tbp(i)=0;
        tt(i)=0;
        tc(i)=0;
        D(i)=0;
        db(i)=0;
        cb(i)=0;
    end
end
N=N(N>0);
bf=bf(bf>0);
hf=hf(hf>0);
W=W(W>0);
tbp=tbp(tbp>0);
tt=tt(tt>0);
tc=tc(tc>0);
D=D(D>0);
db=db(db>0);
cb=cb(cb>0);
cl=get(handles.class,'value');
Be=get(handles.Bear,'value');
fl=get(handles.fluid,'value');
mod=get(handles.model,'value');
```

```
switch fg
    case 1
        so=[bf,hf,N,W,tbp,tt,tc,D,db,cb];
        set(handles.run,'data',so);
end
cla=[1.9    7    7
    1.84   6    8
    1.8    5    8.5
    1.76   4    9
    1.7    13   10
    1.65   2    10
    1.6    2    10
    1.5    2    10 ];
switch cl
    case 1
        H1=cla(1,1);
        H2=cla(1,2);
        max=cla(1,3);
    case 2
        H1=cla(2,1);
        H2=cla(2,2);
        max=cla(2,3);
    case 3
        H1=cla(3,1);
        H2=cla(3,2);
        max=cla(3,3);
    case 4
        H1=cla(4,1);
        H2=cla(4,2);
        max=cla(4,3);
    case 5
        H1=cla(5,1);
        H2=cla(5,2);
        max=cla(5,3);
    case 6
        H1=cla(6,1);
        H2=cla(6,2);
        max=cla(6,3);
    case 7
        H1=cla(7,1);
        H2=cla(7,2);
        max=cla(7,3);
    case 8
        H1=cla(8,1);
        H2=cla(8,2);
        max=cla(8,3);
end
```

```
Bea=[1    1
     1    1
     1    1.2
     1    1.5
     1    2
     0.7 .85
     1.6  1  ];
 switch Be
     case 1
        switch fl
             case 1
        B1=Bea(1,1);
        B2=Bea(1,2);
            case 2
        B1=Bea(2,1);
        B2=Bea(2,2);
            case 3
        B1=Bea(3,1);
        B2=Bea(3,2);
            case 4
        B1=Bea(4,1);
        B2=Bea(4,2);
            case 5
        B1=Bea(5,1);
        B2=Bea(5,2);
        end
     case 2
        B1=Bea(6,1);
        B2=Bea(6,2);
     case 3
        B1=Bea(7,1);
        B2=Bea(7,2);
 end
 sum=0;
 sum1=0;
 for i=1:length(N)
     J2(i)=(60/N(i))^H1*(1/(1+H2/2))*(max-
(W(i)/db(i)))/(max-4);
     tH(i)=tbp(i)/(J2(i)*hf(i)*(1+H2/2*hf(i)));
     J3(i)=(60/N(i))^B1*(4*db(i)/W(i))^B2;
     tB(i)=tbp(i)/(J3(i)*bf(i));
     tb1(i)=J2(i)*tH(i)*hfn*(1+H2/2*hfn);
     tb2(i)=J3(i)*tB(i)*bfn;
     CF1(i)=(cb(i)+cr*tt(i)+cr*(tb1(i)+tc(i)))/D(i);
     CF2(i)=(cb(i)+cr*tt(i)+cr*(tb2(i)+tc(i)))/D(i);
     switch mod
         case 1
```

```
            tb(i)=tb2(i);
            CF(i)=CF2(i);
        case 2
            tb(i)=tb1(i);
            CF(i)=CF1(i);
    end
    sum=sum+CF(i);
    sum1=sum1+D(i);
    cc(i)=sum;
    dd(i)=sum1;
 end
so=[D';J2;tH;J3;tB;tb;CF]';
set(handles.runn,'data',so);
figure
plot(cc,dd,'linewidth',3)
title('Drilling cost Vs. Depth','fontsize',16);
ylabel('Depth,ft','fontsize',16);
xlabel('Cost per Foot,$/ft','fontsize',16)
set(gca,'ydir','reverse');
```

# NOMENCLATURES:

## FOR ROP:

a1 = Formation strength constant

a2 = Normal compaction constant

a3 = Under compaction constant

a4 = Pressure differential constant

a5 = Bit weight constant

a6 = Rotary speed constant

a7 = Tooth wear constant

a8 = Hydraulic constant

d = Bit diameter, in

dn = Bit nozzle diameter, in

D = Well depth, ft

gp = Pore pressure gradient lb/gal

h = Fractional tooth wear

H1 = Constants that depend on bit type

N = Rotary speed, rpm

q = Flow rate, gal/min

W/d = Weight on bit per inch of bit diameter, 1,000 lb/in.

WOB =Weight on bit

RPM= Revolution per Minute

db =Bit Diameter

K= Constant of Proportionality

S= Compressive Strength of the Rock

a5= Bit Weight Exponent

Deq =Equivalent Depth (ft)

Fjm = Modified impact force

$\mu$ = mud viscosity

a,b,c=constant

## FOR HYDRAULIC:

D= Depth (ft

μe = Effective viscosity

dp = Particle diameter

ρp= Particle density

P = Pressure (psia)

Q =Flow rate (gpm)

Ps =Surface Pressure Loss (psi)

SE =Surface Pressure Coefficient

ρ =Mud Density (lb/gal)

L =Surface equipment equivalent length of drill pipe (ft)

Ldp =Length of drip pipe (ft)

Yp =Yield Point (Ibs/100ft)

Pv =Plastic Viscosity (cp)

Ldc =length of drill collar (ft)

ID =Internal diameter (in)

OD=Out diameter (in)

Pc=Circulation Pressure Loss (psia)

Vn= Nozzle velocity

dn= Nozzle diameter

BHHP =Drill Bit Hydraulic Horse Power (hp)

Pmax = Maximum Pump Pressure (psia)

Pc.opt =Optimum Parasitic Pressure Drop (psia )

Pbit.opt, Pbo =Optimum Pressure Drop on the Drill Bit (psia)

BHHP =Optimum hydraulic horse power at the drill bit (hp)

IF =Jet Impact Force (Ibf)

TFA = total open flow rate area (in2)

Q.opt =Optimum Flow Rate (gpm)

dn.opt =Optimum Nozzle Diameter (in)

Va,V' =Average velocity (ft/sec)

RN =Reynolds number

F =Frictional factor

Dop =Outer diameter of the drill pipe or drill collar (in)

Dh = Diameter of the hole (in)

Dp =Diameter of the Pipe (in)

De =Equivalent Diameter of the Drill Collar (in)

n = Power law index

k = Equivalent centipoise

A =Area of Nozzle (in2)

Cd =Discharge coefficient

Pdc= Pressure Drop across Drill Collar (psia)

## For Bit Selection:

CF =Drilling cost per footage

τH =The formation abrasiveness constant

tb = bit run

$\tau B$ = bearing constant, hr

B1,B2 =Bearin wear parameter

W =Weight on bit (Ib)

N = Rotary speed (rpm)

## Cost analysis:

K = constant, ft /hr

A = constant, $ft^{-1}$

D = total depth, ft