Petroleum and Coal

Article **Open Access**

Optimization and Modeling of the Rate of Penetration in an Extended Reach Drilling Process

Igwilo K. Chinwuba, Odo J. Emeka, Uwaezuoke Nnaemeka, Ihedilionye G. Soromtochukwu, Nwaneri P. Chibuzor*

Department of Petroleum Engineering, Federal University of Technology, P.M.B 1526, Owerri, Nigeria

Received December 31, 2019; Accepted March 21, 2020

Abstract

Whereas extended reach drilling is an option, drilling optimization is important as it saves rig time and operational expenditure, hence, maximizes profit. Limited weight on bit, inclined, and horizontal hole cleaning and wellbore stability are common problems in extended reach wells. The rate of penetration plays a key role in optimizing the drilling process, and some attempts have been made towards obtaining a mathematical rate of penetration model for a vertical well. In this work, the Bourgoyne and Young model was modified to account for drilling parameters in extended reach drilling such as bit hydraulics, hole cleaning, and cuttings transport. Drilling optimization techniques were then applied to optimize controllable parameters during the drilling operation to obtain a maximal rate of penetration. The proposed model from this modification was derived from multiple regression analysis using the method of least squares and selected field data. The model was validated using field data, and sensitivity analysis were performed. The rotary speed and weight on bit showed a linear relationship with the rate of penetration. An R-squared value of 98.68% and a mean square error of 1.0555% showed that the proposed model exhibits a reasonable accuracy in the determination of the penetration rate for an extended reach well.

Keywords: *Extended reach drilling; Modeling, Multiple regression analysis; Optimization; Rate of penetration.*

1. Introduction

A hydrocarbon prospect is pinpointed with the aid of geological studies and seismic evaluations. But the most effective way to ascertain the presence of oil or gas in the prospect is to drill a borehole. Drilling is arguably the most expensive portion of the entire exploration and production process [1]. The oil and gas industry gives a lot of focus on the optimization of the drilling process such that oilfield development is carried out in cost-efficient means [2]. Various methods have been developed over time to access hydrocarbon prospects at the subsurface, and these methods have evolved in technicality as accessing these prospects become even more difficult. One of such methods is the Extended Reach Drilling (ERD). Extended reach wells may be very long (measured depth) and quite shallow vertically, or relatively short and very shallow vertically - and everything in the middle. The long reach wells are drilled to far-off reservoirs to cut down on the required infrastructural and operational resources for reservoir access. The relatively short reach wells are drilled in very shallow reservoirs to allow for the necessary reservoir inflow area [3].

Drilling extended-reach wells can be costly and technically demanding. However, they can add significant value to drilling activities by eliminating the need for costly subsea equipment and pipelines. Present industry challenges are greatly affecting drilling operations and total expenditure. Companies without accurate, well-timed, and integrated information may find it difficult to optimize well production, make use of a central archive of data for historical and real-time analysis, or achieve efficient field production monitoring and enhancement leading to below-par performance. The whole idea of optimization is to make use of one or more well records as a basis for the calculation and application of optimum techniques to subsequent wells, so as to reduce drilling costs for subsequent drilled wells. With the progress of the drilling operation in a new area, the drilling crew becomes familiar with the area, and the drilling process can be optimized to reduce the cost of drilling subsequent wells [4]. Rate of Penetration is a key parameter controlling drilling/rig time; therefore, optimization of the rate of penetration will significantly cut down the cost of drilling activities as well as the time to reach the target depth. Optimization of drilling operation can be achieved by increasing the rate of penetration [5], and hence, the time to reach target depth. A high rate of penetration in safe and stable drilling conditions is the key focus and objective of the optimization process.

However, in an Extended Reach Drilling process, parameters such as hole cleaning have significant effects on the Rate of Penetration. Efficient cuttings transport is a key problem when drilling an extended reach well with a horizontal and highly inclined section, and must, therefore, be taken into account in any analysis of the drilling process.

1.1. Extended reach wells

There is no globally accepted definition for extended reach wells, and therefore, it remains a debatable subject till date. As a result of this, there exist various definitions of extended reach wells. Extended reach wells can be commonly described in terms of two distinct ratios, the Unwrapped Reach Ratio and the Depth Ratio [6]. The ratio of the along-hole departure to the true vertical depth (TVD) at measured depth is known as the Unwrapped Reach Ratio. At ratios greater than 2, the well is said to be an extended-reach well. The Depth Ratio, however, is the ratio of the measured depth (MD) of the well to its True Vertical Depth. Furthermore, if the ratio is greater than 2, the well is said to be an extended-reach well. In the early 1980s, Mobil Oil Company first made use of this term for directional wells in which the ratio of the horizontal departure (HD) attained at measured depth (MD) to the true vertical depth (TVD) is greater than or equal to two [7].

1.2. Factors affecting the rate of penetration

The advancement of a drilled borehole is attributed to the failure of the rock beneath the drill bit and the removal of the resulting debris by the drilling fluid. Rock failure depends upon a bit tooth penetrating the formation when using a roller-cone bit [8]. Obviously, the drilling rate should depend on several factors. These factors are;

i. Bit type
ii. Formation characteristics
iii. Operating conditions (Weight on the bit and Rotary speed)
iv. Bit tooth wear
v. Bit Hydraulics
vi. Drilling fluid properties

There are three models most commonly used in the prediction of the rate of penetration in vertical wells; (i) Galle and Woods, (ii) Maurer, and (iii) Bourgoyne and Young.

The breakthrough in drilling technology, as regards the optimization process was pioneered by Galle and Woods [9]. They made the following assumptions; that only two parameters (weight on bit and rotary speed) affect the rate of penetration and that the other variables such as drilling fluid properties, bit hydraulics, etc., were properly selected. Similarly, a model for determining the drilling rate for roller-cone bits from rock cratering mechanisms was developed [10]. This model holds only when all of the rock debris is being removed from the bottom of the wellbore, a condition known as "perfect hole cleaning". Also, multiple regression analysis techniques by the use of detailed drilling data to derive a mathematical model capable of determining the drilling rate, based on various parameters such as formation depth, formation strength, formation compaction, the pressure differential across the bottom hole, bit diameter and bit weight, rotary speed, bit wear, and bit hydraulics have been utilized [11]. Other mathematical models were also developed to determine the best constant weight on bit, rotary speed, and optimum hydraulics for a single bit run so as to attain the lowest possible cost per foot. The method also predicts the drilling time as well as the wear on the bit. The most widely accepted (dominant) model in the drilling industry that makes use of drilling models for drilling rate prediction is the Bourgoyne and Young Model (BYM). It is one of the most comprehensive models. The rate of penetration model is given as Equation (1);

$$\frac{dD}{dt} = exp(a_1 + \sum_{j=2}^{8} a_j x_j) \quad (1)$$

where D =depth and t=time.

1.3. Cuttings transport and hole cleaning in extended reach drilling

The removal and transportation of rock cuttings from the bottomhole to the surface is a major function of drilling fluids [12]. Inefficient hole cleaning in drilling extended reach wells causes some costly problems such as slow rate of penetration, premature bit wear, formation fracture, high torque, and drag, and stuck pipe. Studies on cuttings transport have gone on since the 1940s, and the terminal velocity for single phase drilling fluids was the main focus of previous investigations. The terminal velocity was sufficient to address some hole problems because most of the wells were vertical. Studies were later changed to experimental approaches and mechanistic models, with the growing interest in directional and horizontal wells, whose objective was to describe the cuttings transport phenomenon for all inclination angles [13-14].

Cuttings transport in extended reach wells is far more critical than that of vertical wells. There are two main challenges faced in extended reach wells that are not present in vertical wells. One such challenge is the existence of a bed of cuttings on the low side of the borehole. The other challenge is the sliding nature of the cuttings within the wellbore. At inclination angles of 40º-60º, the bed of cuttings may become unstable due to its tendency to backslide. An unstable cuttings bed puts the drill string at risk, especially whenever mud circulation stops [14-15]. Another problem is the inefficient transport of cuttings, which creates excessive drag and torque (drag is the frictional force caused by pipe movement while torque is a measure of the force causing pipe rotation in the wellbore). This brought about the introduction of three other parameters:

i. Dimensionless cuttings bed area, $\frac{A_{bed}}{A_{well}}$

ii. Dimensionless velocity, $\frac{V_{actual}}{V_{critical}}$

iii. Annular cuttings concentration, C_c

The cuttings bed height is believed to be of great importance to the overall hole cleaning performance and the success of the entire drilling operation. The area of the cuttings bed A_{bed} can be expressed as a dimensionless function as Equation (2):

$$\frac{A_{bed}}{A_{well}} = k_1 (C_c)^{k_2} (N_{Re})^{k_3} \left(N_{fr}\right)^{k_4} \quad (2)$$

where C_c is the annular cuttings concentration; N_{Re} is the Reynolds number and N_{fr} is the Froude number [13].

The cuttings transport ratio is used to estimate the cuttings transport efficiency and is given as Equation (3):

$$\frac{V_{actual}}{V_{critical}} \quad (3)$$

where V_{actual} is the actual annular fluid velocity and $V_{critical}$ is the critical fluid velocity; a function of cuttings slips and lift velocity.

The annular cuttings concentration is defined by Equation (4);

$$C_c = \frac{Net\ volume\ occupied\ by\ cuttings}{Total\ annulus\ volume} \quad (4)$$

Higher cuttings transport ratios indicate a relatively lower cuttings concentration in the borehole [16].

Smaller cuttings result in greater annular cuttings concentrations than larger cuttings in a horizontal annular section and are more difficult to transport in horizontal wells than in vertical wells. They also stick easily to the pipe due to their cohesive effects and are more difficult to free once stuck. Therefore, smaller cuttings would require a much higher fluid velocity to continue the forward movement and erode the cuttings bed [17].

1.4. Optimization

The basic application of drilling optimization is to obtain the highest degree of efficiency possible under certain specific conditions, with the aim of achieving the greatest or least possible outcome of an objective function. Therefore, the optimization process involves the creation of an objective function, detection of controllable variables, both independent and dependent, and several technological and technical constraints.

The drilling optimization process is designed to optimize controllable drilling variables, including weight on bit and bit rotary speed, so as to obtain the highest possible rate of penetration since the drillability of the rock decreases with increasing hole depth [4].

2. Materials and method

2.1. Selection and normalization of relevant field data

Relevant field data was sourced for and stored in an excel file. These sourced data were then converted to their normalized values (standard field units) for easier manipulation. The obtained data include depth (TVD and Measured depth), weight on bit, equivalent circulating density, rotary speed, pore pressure, bit tooth wear fraction, rate of penetration, cuttings concentration, flow rate, mud viscosity and so on. A data file was then created for use in multiple regression analysis.

2.2. Research approach

2.2.1. Multiple regression analysis

For the purpose of this work, the method of least squares was applied (in place of Bourgoyne and Young's matrices approach) using the Multiple Regression Technique. The MS Excel (version 2010) application was used to determine the regression coefficients of the proposed rate of penetration model. The use of regression analysis of past drilling data in the evaluation of constants in a rate of penetration equation is quite popular. Nevertheless, the majority of the past works in this field have been limited due to the difficulty in obtaining large volumes of accurate field data, and as a result of this, the effects of most of the drilling parameters were overlooked.

For a dependent variable (y) and a set of independent variables (x_i), the multiple regression model provides a prediction of y from x_i of the form (Equation 5),

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + \varepsilon \tag{5}$$

In regression analysis, MS Excel (version 2010) computes the statistics for a line using the "least squares" method. It determines a straight line that best fits the acquired data, and then returns an array that best describes the line. Theoretically, a regression analysis model calculates for the dispersion of data points based on the sum of squares. The goal of the model is to obtain the least possible sum of squares and draw a line of best fit.

2.3. Development of the proposed model

As proven by Bourgoyne and Young, the effects of bit weight, compaction, rotary speed, tooth wear, etc. on penetration rate are not dependent on one another, and the compound effect can be given as Equation (6):

$$R = \frac{dD}{dt} = (f_1)(f_2)(f_3)(f_4)\dots(f_n) \tag{6}$$

where $(f_1)(f_2)(f_3)(f_4)$ etc., represent functional relations between the rate of penetration and the various drilling parameters. The functional relations used for the proposed model were based on field studies and objectives of the study. For a roller cutter bit, these functional relations are defined as Equations (7) to (14);

$$f_1 = e^{a_1} \tag{7}$$

$$f_2 = e^{a_2(10{,}000 - D)} \tag{8}$$

$$f_3 = e^{a_3 D^{0.69}(g_p - 9.0)} \tag{9}$$

$$f_4 = e^{a_4 D(g_p - p_c)} \tag{10}$$

$$f_5 = e^{ln\left[\frac{\frac{W}{d_b}-\left(\frac{W}{d_b}\right)_t}{4-\left(\frac{W}{d_b}\right)_t}\right]^{a_5}} \quad (11)$$

$$f_6 = e^{ln\left(\frac{N}{100}\right)^{a_6}} \quad (12)$$

$$f_7 = e^{-a_7 h} \quad (13)$$

$$f_8 = e^{ln\left(\frac{\rho Q}{350\mu d_n}\right)^{a_8}} \quad (14)$$

Considering the effects of hole cleaning and cuttings transport in high angle extended reach wells, three extra functional relations were introduced into the proposed model to account for these effects. These are given as Equations (15) to (17);

$$f_9 = e^{ln\left(\frac{A_{bed}}{A_{well}}\right)^{a_9}} \quad (15)$$

$$f_{10} = e^{ln\left(\frac{V_{actual}}{V_{critical}}\right)^{a_{10}}} \quad (16)$$

$$f_{11} = e^{ln(C_c)^{a_{11}}} \quad (17)$$

The proposed model can then be combined into a giant expression which combines each of the variables, which is shown as Equation (18). This is a rather unmanageable equation, however, so it is recommended to look at each of the terms independently (Equations (15) to (17)) and then combine them at the end of the calculation.

The combination of the above equations gives Equation (18):

$$R = \frac{dD}{dt} = exp\left(a_1 + a_2(10{,}000 - D) + a_3 D^{0.69}(g_p - 9.0) + a_4 D(g_p - p_c) + a_5 ln\left[\frac{\frac{W}{d_b}-\left(\frac{W}{d_b}\right)_t}{4-\left(\frac{W}{d_b}\right)_t}\right] + a_6 ln\left(\frac{N}{100}\right) - a_7 h + a_8 ln\left(\frac{\rho Q}{350\mu d_n}\right) + a_9 ln\left(\frac{A_{bed}}{A_{well}}\right) + a_{10} ln\left(\frac{V_{actual}}{V_{critical}}\right) + a_{11} ln(C_c) \right) \quad (18)$$

The proposed model equation is very wordy but depends on the accuracy of the factors $a_1 - a_{11}$ to be able to model drilling performance. The above equation is then converted into a straight line equation so as to fit into the multiple regression equation (Appendix 1.0). A multiple regression analysis was performed on the drilling data using the multiple regression equation to find appropriate values for these regression coefficients.

2.4. Model validation

Initially, the proposed model was validated by carrying out multiple regression analysis with the same field data used by [11] in their analysis. The regression constants for both models were obtained and compared to ensure the accuracy of the proposed model. The following results were obtained;

Table 1: Comparison of regression coefficients

Coefficients	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
B & Y Model	3.78	0.00017	0.0002	0.000043	0.43	0.21	0.41	0.16	-	-	-
Proposed model	3.76	0.000175	0.0002	0.000043	0.42	0.18	0.41	0.16	-	-	-

Table 2. The minimum ranges recommended for regression analysis [15]

Parameters	Minimum range	Parameters	Minimum range
X_2	2000	X_7	0.20
X_3	15000	X_8	0.50
X_4	15000	X_9	0.50
X_5	0.40	X_10	1.7
X_6	0.50	X_11	4.5

A comparison of the results shown in Table 1 indicates that the proposed model and method determines the regression coefficients with a reasonable level of accuracy based on the number of data points which depends on Equation (18) and the range of the values of the available drilling parameters as shown in Tables 2 and 3.

Table 3. The minimum number of data points recommended for the multiple regression analysis [15]

Number of parameters	Minimum number of data points	Number of parameters	Minimum number of data points
11	45	6	20
10	40	5	15
9	35	4	10
8	30	3	7
7	25	2	5

2.5. Sensitivity analysis

The proposed model was subjected to sensitivity analysis by varying the rate of penetration with the various drilling parameters. Some of the plots are shown in Figure 1.

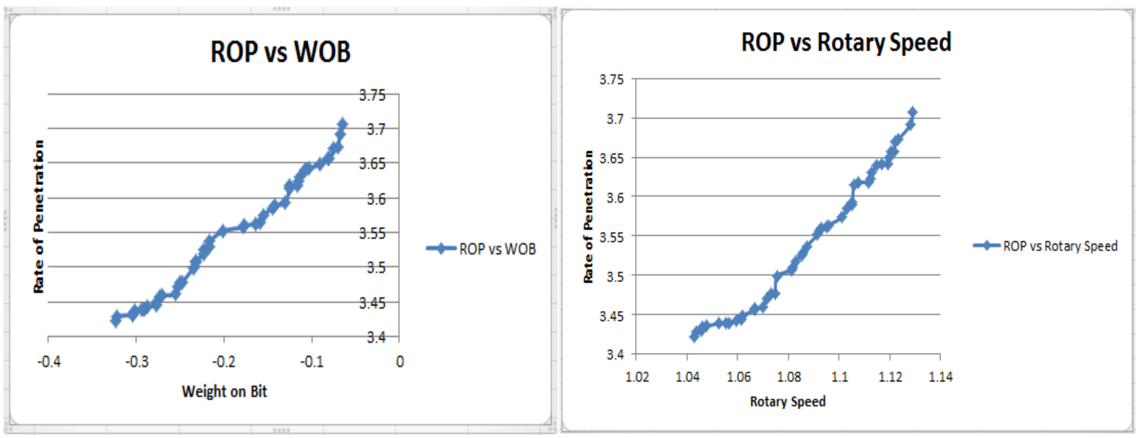

Figure 1. Sensitivity analysis plot of ROP vs. Weight on Bit (left) and ROP vs. Rotary Speed (right)

Figure 1 shows a direct proportionality relationship between the rate of penetration and both weight on bit and rotary speed. Sensitivity analysis of other parameters exhibited jagged plots and was therefore not included.

3. Results and discussion

3.1. Results

The proposed model was initially validated by comparing with the Bourgoyne and Young model, and predicting the rate of penetration using field data available [11]. The results obtained are shown in Figures 2 and 3;

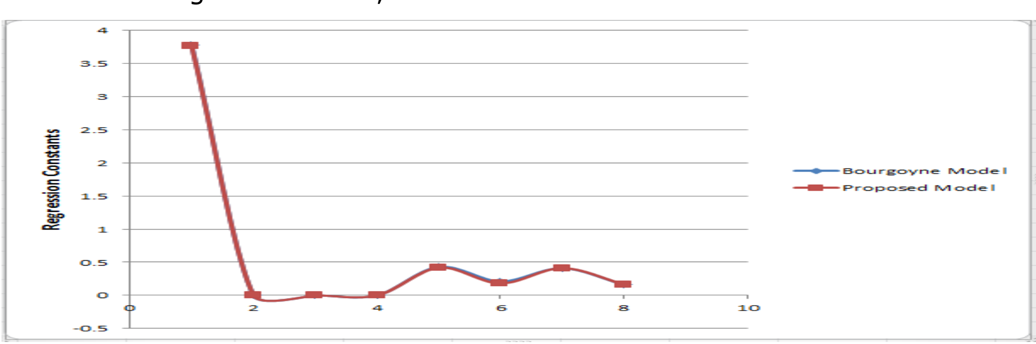

Figure 2. Comparison of regression coefficients of Bourgoyne and Young's model and proposed model

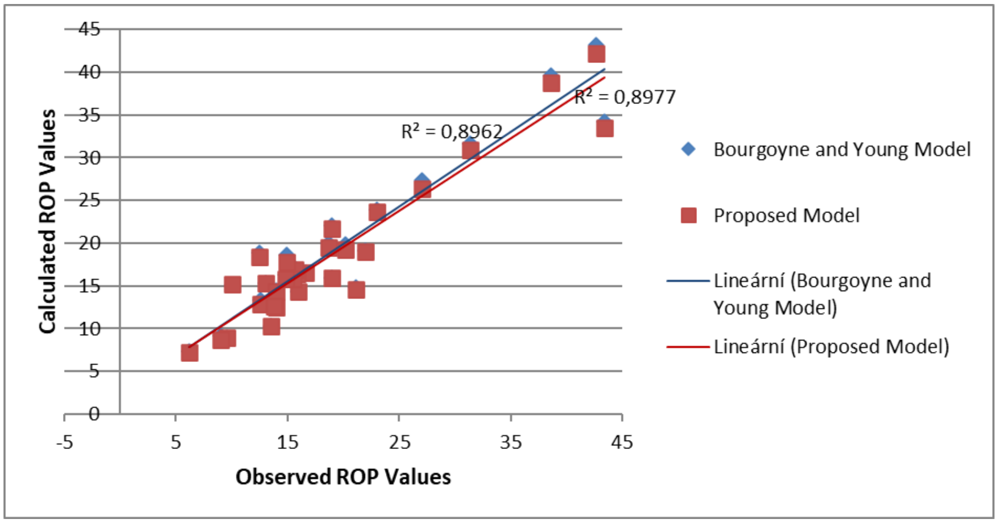

Figure 3. Calculated ROP values (Bourgoyne and Young's model and proposed model) vs. observed ROP values

Figure 3 shows a very close relationship between the regression constants of Bourgoyne and Young's model and the proposed model, as seen in their nearly equal values. This is because the Bourgoyne and Young's model was used as the reference for this study. However, the proposed model was observed to predict the rate of penetration values at a slightly higher level of accuracy than the Bourgoyne and Young's Model. This is seen in the values of the correlation coefficient and mean square error. The coefficient of correlation (Figure 3) for Bourgoyne and Young's model was obtained as **0.9467,** and that of the proposed model as **0.9500**.

The Mean Square Error for both models was obtained from the following correlation (Equation (19));

$$Mean\ Square\ Error\ (MSqE) = \frac{1}{n}\sum_{i=1}^{n}(\ln ROP_{calc} - \ln ROP_{actual})^2 \qquad (19)$$

From Equation (19), the obtained mean square error for the B&Y model was 0.027748, and that of the proposed model was 0.027199, as shown in Figure 4.

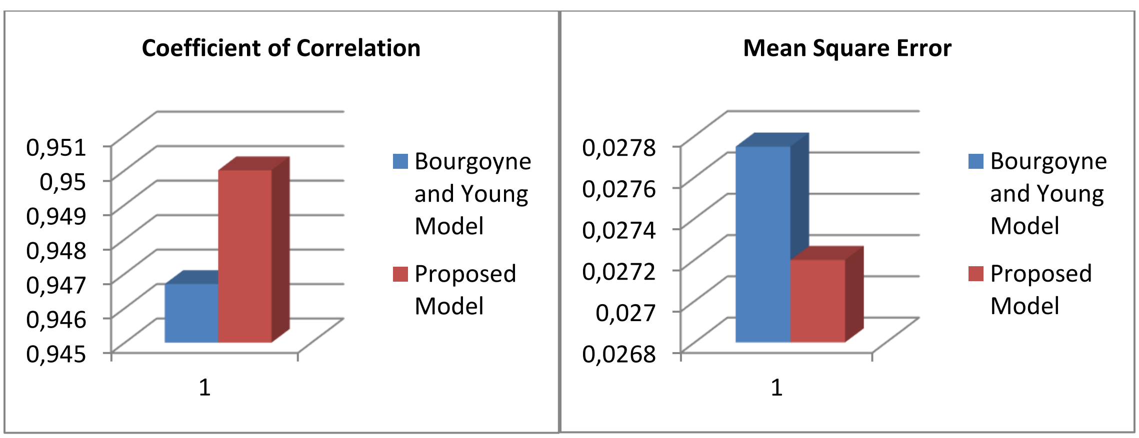

Figure 4. Comparison of correlation coefficient and Mean square error for both models

On validation of the model, the model was applied to a depth interval representative of a single formation. The regression variables were obtained and substituted in the proposed rate of penetration model using the selected drilling data for the model. Multiple regression analysis was then applied to obtain regression coefficients. The following results were obtained;

Table 4. Calculated regression variables and statistical analysis values for depth 6000-8066 ft

Coefficients	Values	Coefficients	Values
a_1	7.815348	a_7	1.454594
a_2	-0.00019	a_8	0.411157
a_3	-0.00145	a_9	2.653928
a_4	-0.000045	a_10	0.000236
a_5	0.527414	a_11	0.012582
a_6	-0.19537		
Multiple R	0.999554		
Adjusted R square	0.986803		
Standard error	0.109414		

From Table 4, the very high value of Multiple R indicates a very strong relationship between the dependent variable (rate of penetration) and the independent variables (drilling parameters) as previously established by authors. The coefficient of determination, Adjusted R squared, indicates that 98.68% of the dependent variables are explained by the independent variables, that is, 98.68% of our values fit the regression analysis model. A low standard error also indicates a greater precision of the regression analysis.

On the determination of the regression constants, the rate of penetration can then be calculated at various drilling conditions. This was done using the selected field data initially used for the comparison of both models (depth interval of 6000 to 8066ft).

The regression index of correlation, G, checks the persistence of Multiple Regression Analysis. It may be defined by Equation (20);

$$G = \sqrt{1.0 - \frac{\sum[\ln ROP_{observed} - \ln ROP_{calculated}]^2}{\sum[\ln ROP_{observed} - \overline{\ln(ROP)}]^2}} \quad (20)$$

The regression index of correlation was obtained as **0.96226** using Equation (20). This value of the correlation index is high and thus shows that the proposed model is a good model. The Mean Square Error obtained was **0.010555**, which indicates a high accuracy.

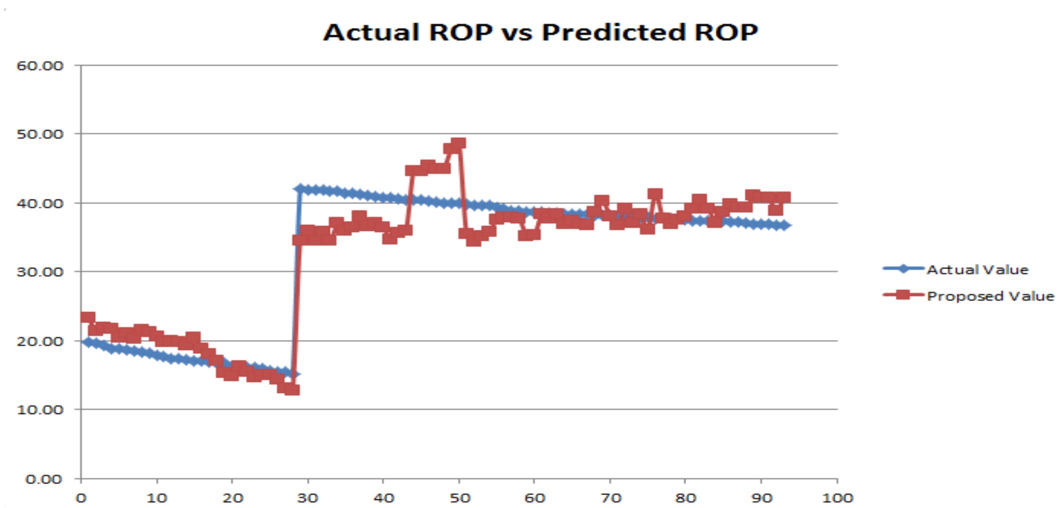

Figure 5. Plot of Actual ROP values and proposed model values

3.2. Optimization of the rate of penetration

After obtaining the regression coefficients and validating the proposed model, the rate of penetration must be optimized in line with the objective of the study. For this purpose, MSExcel Solver, as previously tested and presented for optimization, was utilized to iterate input parameters (regression variables) [18]. Excel solver iterates changing variables so as to minimize, maximize, or maintain the value of an objective function (rate of penetration). The only input parameters that are modified are the controllable mechanical parameters (Weight on Bit and Rotary speed). The Solver was run with the purpose of maximizing the value of the rate of penetration. Upper and lower limits (constraints) were also included in the constraints for the solver, thereby keeping them in prescribed ranges. The program continues iterating until there are no more changes in which the variables can increase the rate of penetration value. At this point, the determined value of ROP is the optimum value under normal drilling conditions. Figure 5 shows the results. For a particular data range, MS Excel Solver (version 2010) was applied, and the optimum rate of penetration was obtained as 38.235ft/hr.

4. Conclusion and recommendation

4.1. Conclusion

A robust model was developed using multiple regression analysis and successfully applied to obtain an authentic solution to predict the rate of penetration for roller cone bits in an extended reach well. The model serves as an efficient tool in the determination of the effects of the drilling parameters on the penetration rate under several technological constraints. The proposed model was tested on field data, and acceptable results were obtained. The rate of penetration was then optimized using MS Excel Solver (version 2010). It obtained maximal values of ROP by varying alterable regression variables such as weight on bit and rotary speed, under various realistic constraints. From the analysis, it could be concluded that after taking hole cleaning parameters in extended reach wells into consideration, the rate of penetration can be predicted with reasonable accuracy using the proposed model, and the optimal rate of penetration values can be obtained by varying controllable mechanical parameters. Also, the method of least squares in regression analysis is observed to be more accurate than matrix regression utilized by Bourgoyne and Young. Similarly, the drillability, depth, and rock strengths are observed to be the main parameters controlling the rate of penetration, and parameters have less significant effects ranked according to their relationships with the penetration rate. Finally, an increase in the weight on bit and rotary speed produced a corresponding increase in the rate of penetration.

4.2. Recommendation

It should be considered that the use of accurate and detailed drilling data to carry out analysis, predictions, and drilling optimization, so as to obtain meaningful results is fundamental. Moreso, the cost of drilling can be considered for the optimization of the rate of penetration in future works. Also, instead of using all acquired data points, a reduced number of data points representative of an existing data trend should be used as it would give much more accurate results in analysis. Lastly, wellbore inclination angles may be accounted for in the study to improve the accuracy of results.

APPENDIX 1.

Derivation of Multiple Regression Equation

$$R = \frac{dD}{dt} = Exp\left(a_1 + a_2(10{,}000 - D) + a_3 D^{0.69}(g_p - 9.0) + a_4 D(g_p - p_c) + a_5 ln\left[\frac{\frac{W}{d_b} - \left(\frac{W}{d_b}\right)_t}{4 - \left(\frac{W}{d_b}\right)_t}\right] + a_6 ln\left(\frac{N}{100}\right) - a_7 h + a_8 ln\left(\frac{\rho Q}{350\mu d_n}\right) + a_9 ln\left(\frac{A_{bed}}{A_{well}}\right) + a_{10} ln\left(\frac{V_{actual}}{V_{critical}}\right) + a_{11} ln(C_c)\right) \quad 1.0a$$

Substituting the variables in the Equation (1.0a) with corresponding x-values gives Equation (1.0b);

$$R = \frac{dD}{dt} = Exp(a_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + a_6X_6 + a_7X_7 + a_8X_8 + a_9X_9 + a_{10}X_{10} + a_{11}X_{11}) \quad 1.0b$$

Taking the Natural logarithm of both sides of Equation (1.0b) gives Equation (1.0c);

$$\ln\frac{dD}{dt} = a_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + a_6X_6 + a_7X_7 + a_8X_8 + a_9X_9 + a_{10}X_{10} + a_{11}X_{11} \quad 1.0c$$

References

[1] Falode OA, Agbarakwe CJ. Optimisation of Drilling Parameters for Directional and Horizontal Wells Using Genetic Algorithm. Journal of Scientific Research and Reports, 2016; 11(3):1-10.
[2] Tuna E. Real-time-optimization of Drilling Parameters during Drilling Operations. Middle East Ph.D. Thesis, Technical University Ankara, Turkey (2010).
[3] Petrowski. Extended Reach Wells (2016). Retrieved December 3, 2019, from Petrowiki: www.petrowiki.org.
[4] Sonny I., Adib M., Abd Rahman AM, & Saleem QT. Optimization of weight on bit during drilling operation based on rate of penetration. Research Journal of Applied Sciences, Engineering and Technology, 2012; 4(12).
[5] Alum MA, Egbon F. Semi-Analytical Models on the Effect of Drilling Fluid Properties on Rate of Penetration (ROP). Nigeria Annual International Conference and Exhibition. Society of Petroleum Engineers, 2011; SPE-150806-MS: https://doi:10.2118/150806-MS.
[6] Agbaji AL. Optimizing the Planning, Design and Drilling of Extended Reach and Complex Wells. Abu Dhabi International Petroleum Exhibition & Conference, UAE. Society of Petroleum Engineers, 2010; SPE-136901-MS: https://doi:10.2118/136901-MS.
[7] Schlumberger. Extended Reach Drilling (2019). Retrieved December 3, 2019, from Schlumberger Oilfield Glossary: www.glossary.oilfield.slb.com.
[8] Ramsey MS. Practical Wellbore Hydraulics and Hole Cleaning. Texas: Elsevier Science (2019).
[9] Galle EM, Woods HB. Best Constant Weight and Rotary Speed for Rotary Rock Bits. American Petroleum Institute- Drilling and Production Practice (1963). API-63-048.
[10] Maurer WC. The "Perfect-Cleaning" Theory of Rotary Drilling. Tulsa, Oklahoma, JPT-Society of Petroleum Engineers, 1962; SPE-408-PA: https://doi:10.2118/408-PA.
[11] Bourgoyne AT, Young FS. A Multiple Regression Approach to Optimal Drilling and Abnormal Pressure Detection. SPE AIME Sixth Conference on Drilling and Rock Mechanics. Austin, Texas: Society of Petroleum Engineers, 1974; SPE-4238-PA: https://doi:10.2118/4238-PA.
[12] Igwilo K, Okoro EO, Ohia PN, Adenubi S, Okoli N, Adebayo T. Effect of Mud Weight on Hole Cleaning During Oil and Gas Drilling Operations: Effective Drilling Approach. The Open Petroleum Engineering Journal, 2019; 12(1):14-22.
[13] Ozbayoglu EM, Miska S, Reed T, & Takach N. Analysis of Bed Height in Horizontal and Highly Inclined Wellbores by Using Artificial Neural Networks. SPE International Thermal Operations and Heavy Oil Symposium and International Horizontal Well Technology Conference. Calgary, Alberta: Society of Petroleum Engineers, 2002; SPE-78939-MS: https://doi:10.2118/78939-MS.
[14] Uwaezuoke N, Onwukwe SI, Igwilo KC, Obah B. Biopolymer substitution and impact on cuttings transport of a lightweight water-based drilling fluid. Journal of Petroleum Engineering and Technology, 2017; 7(2): 54-64.
[15] Ozgouei RE. Rate of Penetration Estimation Model for Directional and Horizontal Wells. Master's Degree Thesis, Ankara: Middle East Technical University, METU 2007. Retrieved December 7, 2019, from https://etd.lib.metu.edu.tr/upload/12608737/index.pdf.
[16] Rooki R, Ardejani FD, Moradzadeh A, Norouzi M. Simulation of cuttings transport with foam in deviated wellbores using computational fluid dynamics. Journal of Petroleum Exploration and Production Technology, (2014; 4(3), 263-273.
[17] Duan M, Miska S, Yu M, Takach N, Ahmed RM, Zettner CM. Transport of small cuttings in Extended Reach Drilling Process. SPE International Oil and Gas Conference and Exhibition, 2013; SPE-104192-MS: https://doi:10.2118/104192-MS.
[18] Uwaezuoke N, Igwilo KC, Onwukwe SI, Obah B. Optimization of *Mucuna solannie* Mud Rheo logical Parameters. Journal of Petroleum Engineering and Technology, 2017; 7(1): 15-26.

To whom correspondence should be addressed: Dr. Uwaezuoke Nnaemeka, Department of Petroleum Engineering, Federal University of Technology, P.M.B 1526, Owerri, Nigeria,
E-mail nnaemeka.uwaezuoke@futo.edu.ng