Petroleum and Coal

Article **Open Access**

Analysis of Factor Effects and Interactions in a Conventional Drilling Operation by Response Surface Methodology and Historical Data Design

Wilson Fidelis Ekpotu[1], Joshua O. Ighalo[2], King-akanimo Bassey Nkundu[3], Precious Ogwo Onu[4], Adewale George Adeniyi[2]*

[1] *Power and Energy Oil Tools Ltd, Port Harcourt, Nigeria*
[2] *Department of Chemical Engineering, Nnamdi Azikiwe University, P. M. B. 5025, Awka, Nigeria*
[3] *Ministry of Petroleum Resources, Calabar, Nigeria*
[4] *Department of Chemical and Petroleum Engineering, University of Uyo, Uyo, Nigeria*

Received June 18, 2020; Accepted September 30, 2020

Abstract

A smooth drilling process can achieve safe and fast well establishment and better investment efficiency. Response surface methodology (RSM) on Design Expert 10.0.1 (Stat Ease Inc., Minneapolis, USA) was utilised for the factor effects and interactions in a conventional drilling operation. The aim of this study was to utilise RSM and historical data design (HDD) was used to model the effect of weight on bit (WOB), hook load and revolutions per minute (RPM) on the rate of penetration (ROP), pressure and torque of drilling. Statistical validation of the data was conducted using Analysis of Variance (ANOVA) Partial sum of squares - Type III. The models for all three responses were statistically significant (at a significance level of $p < 0.05$). At low RPM (80 – 81 Hz) and an intermediate hook load (235 – 240 lb), ROP was observed to be high. It was observed that the torque is optimal anywhere above a hook load of 235 lb. The pressure was highest at high RPM (83 – 85 Hz) and low WOB (8 – 12 lb). From this study, the effects of process factors on drilling parameters have been successfully modelled and investigated.

Keywords: *Drilling; Historical data design; Factors; Response surface methodology.*

1. Introduction

Drilling activities are some of the most essential processes of oil and gas operations [1]. Ranging from Seismic activities to geological and geophysical survey and then exploration activities, the value chain towards the production of crude oil or natural gas from both conventional and unconventional reservoirs cannot be completed without actively having the drilling phase [2]. In this regards, it is therefore pertinent to know that drilling activities have several factors that affect its effectiveness and efficiency. And therefore a clear understanding of the effects of these numerous parameters on drilling operations will help in ascertaining the planning of the entire drilling programme as the case may be [3].

Egbe and Iturrios [4] stated that the continuous demand for hydrocarbons for multiple purposes has led to the necessity of exploring new ways to develop new or existing oil field to keep up with the ever-increasing demand. However, such a strategy comes with its challenges, like formation pressure heterogeneity and rapid change in formation pressure within the same hole section. Accordingly, Abd Rahman [5] emphasized that managed pressure drilling utilizes an underbalanced mud density which when combined with the annular surface pressure, maintains the overbalance condition at all times with a target bottom hole pressure close to the formation pressure.

Han, Sun [6] observed that drilling is one of the most important aspects of resource development. A smooth drilling process can achieve safe and fast well establishment and better investment efficiency [7]. And an accurate rate of penetration (ROP) estimation can benefit the well planning and prevent unexpected drilling accidents [8]. Many parameters influence the instantaneous ROP, including formation properties, mud rheology, drill bits, and bit/rock interactions. String vibrations, deformations, and bit fatigue can also affect the rate of bit penetration [9].

Therefore, factors such as the rate of penetration (ROP), revolutions per minute (RPM) of the bit, weight on bit (WOB), hook load, pressure and torque are generally critical to ensuring that drilling operations are carried out with standard international drilling practices.

These variables play a very critical role in ensuring that drilling rate is being improved and can also be a major factor in impeding the ultimate progress of drilling operations if it leads to adverse effects such as wellbore caving in, and an indefinite downhole problem that will trigger more drilling cost and increase downtime which could have been averted [10]. It is worthy of note that these drilling parameters enlisted can be adjusted and recalibrated to suit the formation being drilled offshore or onshore, thus reducing drilling difficulties at different zones and scenarios [11].

The weight on bit (WOB) is the difference of weight force of the part of the drill string below the neutral point and the buoyancy force of drilling mud [12]. Increasing WOB can enhance the rate of drill bit penetration. Nevertheless, increasing WOB may lead to buckling of the drill string. Buckling causes permanent contact of a drill string with the borehole wall and leads to corrosion and failure in both of them [12]. In 1974, Bourgoyne and Young developed a multi regression model to estimate ROP [13]. Weight on bit, rotary speed, bit wear, bit size, hydraulics Formation depth, strength, and over/under balance conditions were used for rate of penetration calculation. Rock/bit interactions, bit properties, fluid properties were also considered in their model [6].

For developing advanced real-time analysis, rate of penetration (ROP) prediction is always one the most key aspects among drilling engineers, because it makes the possibility to optimize drilling parameters to achieve the minimum cost per foot [14]. Moraveji and Naderi [15] emphasized that the prediction and optimization of the penetration rate will be crucial to be able to reduce the cost of drilling operations. However, Cheatham and Nahm [16] specified that overall drilling costs can be reduced in slow drilling formations by increasing ROP. Therefore, this states the role and effect of ROP and specific other drilling parameters in drilling operations.

Generally, according to Jahanbakhshi, Keshavarzi [14], in many studies, factors affecting the ROP have been grouped as follows:

a) Formation characteristics (e.g. hardness and/or abrasiveness (drillability), underground formations stress, pore pressure, porosity and permeability)
b) Mechanical factors (e.g. weight on bit, bit type and rotary speed)
c) Hydraulic factor (e.g. bit hydraulic power, pump pressure, bottom- hole cleaning)
d) Drilling fluid properties (e.g. mud weight, viscosity, filtrate loss, solid content, yield point, gel strength, mud pH)
e) Drilling operation (e.g. hole size, equivalent circulating density)

A combination of the above-mentioned factors influencing ROP while some of them are controllable but the others are uncontrollable. Formation as nearly an independent or uncontrollable variable is influenced to a certain extent by hydrostatic pressure. Laboratory experiments indicate that in some formations any increase in hydrostatic pressure cause to increase the formation hardness or reduces its drillability. The bit type selected, i.e., whether a drag bit, diamond bit, or roller cutter bit can somewhat affect the ROP obtainable in a given formation. Also, the mechanical factors of weight on the bit and rotary speed are then linearly related to ROP.

Within the scope of the authors' exhaustive search, Historical Data Design (HDD) on Response Surface Methodology (RSM) have not been employed in factor analysis for drilling operations. To further emphasize on the novelty of this work, Response Surface Methodology has not been used for the analysis of a conventional oil field drilling data such as weight on bit (WOB), hook load, rate of penetration (ROP), revolutions per minute (RPM), pressure and torque. Hence, this work seeks to analyse the factor effects and interactions in a conventional field drilling operation by Response Surface Methodology (RSM) and Historical Data Design (HDD).

2. Materials and methods

2.1. Method

Response surface methodology (RSM) is a group of statistical technique used for modelling and optimisation [17-18]. It can also be used for investigating factor effects and interactions on a process system [19]. In this study, RSM on Design Expert 10.0.1 (Stat Ease Inc., Minneapolis, USA) was utilised for the factor effects and interactions in a conventional drilling operation. The used in the study was on the mechanical parameters for the drilling operation of a conventional oil well. The key factors were WOB, hook load and RPM while the responses were ROP, pressure and torque. There were 999 lines of data for the analysis.

2.2. Data analysis

RSM was used to investigate the effect and interactions between WOB, hook load and RPM on the ROP, pressure and torque in a drilling operation. In this regard, the total force pulling down on the hook that includes the weight of the drill string in air, the drill collars and any ancillary equipment is referred to as the hook load. Similarly, the ROP is the speed at which the drill bit can break the rock under it and thus deepen the wellbore. However, the data analysis was inputted into Design Expert 10.0.1 (Stat Ease Inc., Minneapolis, USA) using the Historical Data Design (HDD). HDD allows the flexibility of specifying the number of factors, number of responses and the number of data lines. It is especially suitable for the analysis of a historical dataset in which these variables are already available and are outside the control of the researcher. Historical data design has been previously utilized for the optimization of biodiesel production [20], machining condition [21], solvent extraction [22], photo-catalysis [23], etc. Statistical validation of the data was conducted using Analysis of Variance (ANOVA) partial sum of squares - type III. The effects and interactions were visualised using both contour plots and surface plots. The variables used in the study is summarised in Table 1.

Table 1. Designation of factors and responses for the study

Designation	Data (x)	Unit	Data band
Factor 1	Revolutions per minute (RPM)	Hz	$80 < x < 85$
Factor 2	Weight on bit (WOB)	Lb	$8 < x < 25$
Factor 3	Hook load	Lb	$225 < x < 245$
Response 1	Rate of Penetration (ROP)	Ft/min	-
Response 2	Torque	Nm	-
Response 3	Pressure	Psi	-

3. Results and discussion

3.1. Statistical validation of the response surface model

Analysis of variance (ANOVA) partial sum of squares - type III was used to validate the research data. The ANOVA tables are shown in the Appendix. From the results, it was observed that all three response surface models were statistically significant (at a significance level of $p < 0.05$). Furthermore, the best fit model for ROP was the response surface sixth model. Response surface fifth model was the best fit for torque while the quartic model was the best fit for pressure. The lack-of-fit was also not significant for all three models which further reinforces the accuracy and suitability of the modelling study. The values on the y-axis of in the response plots for investigating the effects and interactions must be ignored as they are not actually the exact values because the model is a non-hierarchical polynomial regression model (and it excludes hierarchically inferior terms). The plots are chosen in such a way that all factors are discussed and all key factor interactions are highlighted.

3.2. Factor effects and interactions on ROP

In most of the studies, the rate of penetration (ROP) has been considered as the objective function of the optimization process. ROP depends on many factors including well depth, formation characteristics, mud properties, the rotational speed of the drill string, etc. [24]. Zhao,

Noorbakhsh 24 stated that several studies have been conducted to gain a profound insight into the effective parameters on ROP. ROP is affected by several parameters, which can be categorized into controllable and uncontrollable parameters [25].
For developing advanced real-time analysis, rate of penetration (ROP) prediction is always one the most key aspects among drilling engineers, because it makes the possibility to optimize drilling parameters to achieve the minimum cost per foot. Besides, ROP models can be used to estimate formation drillability by considering the effects of drilling parameters, bits design and bit wear [14]. The effect of WOB and RPM on ROP is shown in Figure 1. It can be observed that when WOB and RPM are low, this results in a low ROP. Similarly, when WOB and RPM are high, a low ROP is also observed. The Weight on Bit (WOB) and Revolutions Per Minute (RPM) are direct factors that can affect the Rate of Penetration (ROP) in a conventional and an unconventional drilling formation because they improve the optimal functionalities of the drill bit that therefore improves the rate at which penetration occurs through the formation. The region of optimality lies adjacent to these two earlier described regions and shown by the red areas on the surface in Figure 1. ROP was observed to the optimum at low RPM (80 – 81 Hz) and high WOB (20 – 25 lb) and high RPM (83 – 85 Hz) and low WOB (8 – 14 lb).

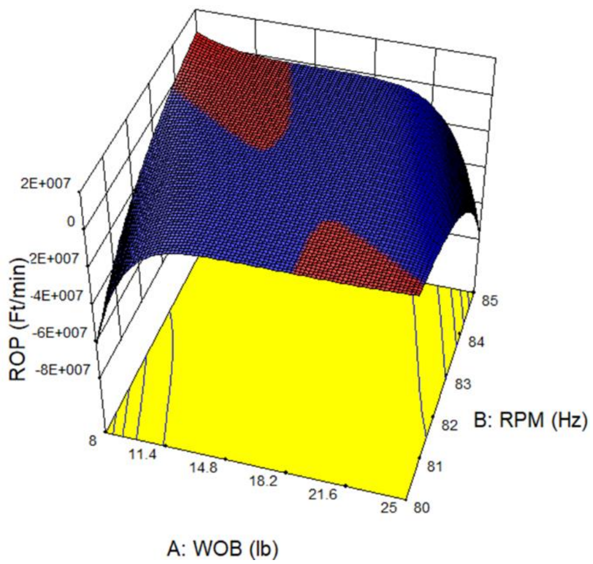

Figure 1. Effect of WOB and RPM on ROP

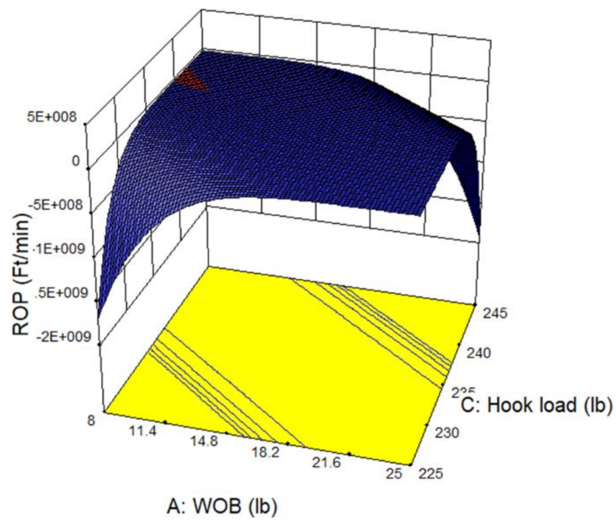

Figure 2. Effect of WOB and hook load on ROP

The RPM and WOB are consistent factors that have seemingly interchangeable effects but same results and as thus they vary are different sections of the formation geometry and specific formation points for this conventional reservoir formation dataset allowed for optimum ROP once one of the active parameters peaked individually, and hence accounting for an optimum ROP at a high WOB and a low RPM and thereafter still optimal at a high RPM and a low WOB. Alum and Egbon [26] stipulated that ROP is mostly obtained real-time and it is often difficult to predict. This is because the factors controlling ROP are numerous and dependent on so many others, also some factors are not complementary (rather they are complex and non-linear) meaning an increase in one may lead to a decrease in the other, the overall effect then reflecting in ROP.

The effect of WOB and hook load on ROP is shown in Figure 2. It can be observed that when WOB and hook load is low, this results in a low ROP. Similarly, when WOB and hook load is high, a low ROP is also observed. The effectiveness of the Rate of Penetration (ROP) is also critically hinged on the Weight of Bit and the hook load as the weight on bit acts as a vertically aligning force that conveys the bit in enabling a penetration increase through the different layers of the formation. Consequently, if the WOB and Hook load are both low, the ROP will gradually decline while also being cushioned by the other parameters. Hence an increased bit weight can stimulate a maximum penetration rate. The ROP was observed to be optimum at an intermediate hook load (235 – 240 lb) but low WOB (8 – 10 lb).

The effect of RPM and hook load on ROP is shown in Figure 3. The optimal regions can be observed by the red areas on the response surface. At low RPM (80 – 81 Hz) and an intermediate hook load (235 – 240 lb), ROP was observed to be high. The result shows that at a practical intermediate hook load level of between (235 – 240 lb), the ROP (Rate of Penetration) was increased even with the RPM being low, and this is because the variability and non-linear nature of the data set accounts for only an increased ROP when the hook load (a mechanical property) was at an intermediate position at a specific formation interval that generated a low RPM. Furthermore, at high RPM (83 – 85 Hz) and an intermediate hook load (230 – 235 lb), ROP was observed to be high. Alum and Egbon [26], factors controlling ROP (including hook load and RPM) are dependent and are not complementary (rather they are complex and non-linear), and this accounts for the switch between the high and low nature of the RPM and the hook load and their responses on the ROP.

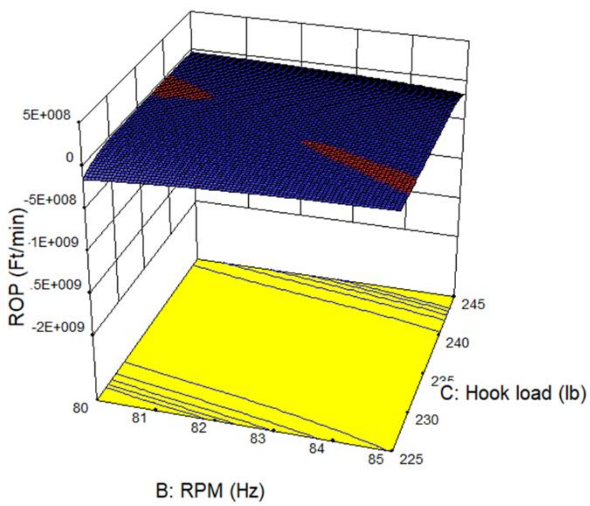

Figure 3. Effect of RPM and hook load on ROP

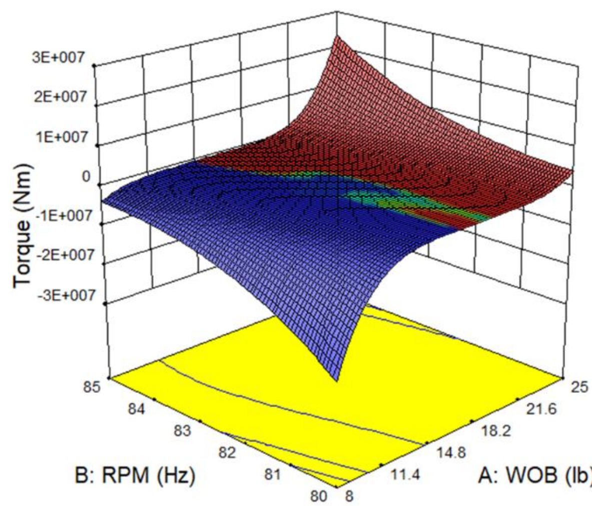

Figure 4. Effect of WOB and RPM on Torque

3.3. Factor effects and interactions on torque

Drilling Torque is a measure of the cumulative force that can directly cause the drill bit to rotate vertically into the formation axis and could also engage angular acceleration as in the case of directional drilling in certain fields. The effect of WOB and RPM on torque is shown in Figure 4. It can be observed that the torque increases with increasing WOB and this is because torque uniquely refers to the rotational equivalent of linear force, which in this case is the twist of the drill bit around a particular formation axis and as such when the WOB and RPM increases the torque also increases proportionally. A synergistic effect of WOB and RPM is observed as the torque becomes quite high at high values of each of the parameters. Torque was optimal anywhere above WOB of 15 lb and was maximum at the highest values of both factors. Schamp, Estes [27] emphasized that the torque required to rotate generally arises from two sources: the frictional resistance between the rotating drill string and the casing or bore-hole and the bit/stabilizer torque. Hence, the frictional resistance between the rotating drill string is a direct reflection of the RPM which is inter-dependent on the WOB.

An increase in Weight-on-bit (WOB) may increase ROP for some time but may lead in faster Bit wear and dulling, which will then reduce ROP in the long run, hence making optimization difficult [26]. The effect of WOB and hook load on torque is shown in Figure 5. A synergistic effect of both factors can be observed as increasing values of both factors increased the torque. Minimal torque was achieved at the lease values of WOB and hook load while maximum torque was observed at the highest values of both factors. Therefore, a direct and proportional increase in the Weight-on-bit and the hook load ensures an increase in the drilling torque for the given hole section.

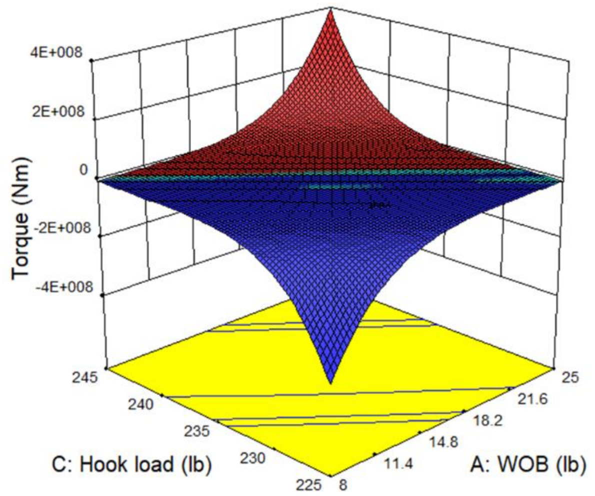

Figure 5. Effect of WOB and hook load on Torque

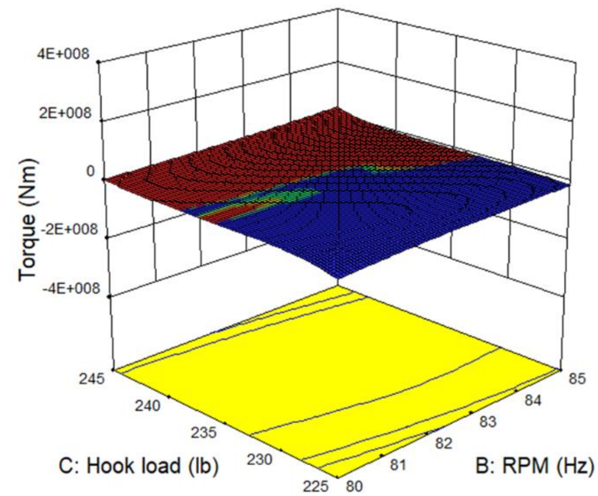

Figure 6. Effect of RPM and hook load on Torque

The effect of WOB and hook load on torque is shown in Figure 6. It can be observed that the torque is optimal anywhere above a hook load of 235 lb. In line with this, optimal drilling torque can only be achieved at an accelerated hook load resident at above 235 lb and beyond given the pre-defined reservoir data set, because the two variables are simply reliant on the forward nature of the other. In this domain, RPM had a minimal interactive effect with WOB as it affects the torque.

3.4. Factor effects and interactions on pressure

Affirmatively, van Riet, Reitsma [28] stated that accurate control over bottom hole pressure during drilling is essential as the industry operates in an increasingly challenging drilling environment. Similarly, in conventional drilling, the downhole pressure is composed of the following two main components:

1. The hydrostatic pressure of the mud column including cuttings (P_{stat}).
2. The hydrodynamic pressure in the annulus induced by various effects such as mud flow or drill pipe movement (P_{dyn}).

Therefore, uncertainties in pore pressure can also lead to an influx of unwanted reservoir fluids into the wellbore [4], and the WOB and RPM will not effectually have a direct impact on the pressure during drilling. The effect of WOB and RPM on pressure is shown in Figure 7. The pressure is observed to be low at high RPM and high WOB. The pressure was also low at low values of both factors. Pressure is a precise parameter in drilling operations and this comes in different forms, and one of those primary forms is the pressure ranging from pumping operations of the drilling fluids through the drill bit nozzles to the mud return rate towards the mud tanks through the annulus, hence WOB and RPM are implicit variables and hence even if pressure is low, the Response Surface methodology represents a non-effect of these parameters on pressure. The region of optimality was observed at the diagonal between these factors. Pressure was highest at high RPM (83 – 85 Hz) and low WOB (8 – 121 lb).

The effect of WOB and hook load on pressure is shown in Figure 8. Pressure is observed in this case to be low at high hook load and high WOB. Pressure was also low at low values of both factors. The critical variable here to be looked out for is the WOB which has an impact on the pressure in this case at both high and low levels as shown by Figure 8. The region of optimality was observed at the diagonal between these factors. These areas are where a factor was kept and the other kept low and vice versa.

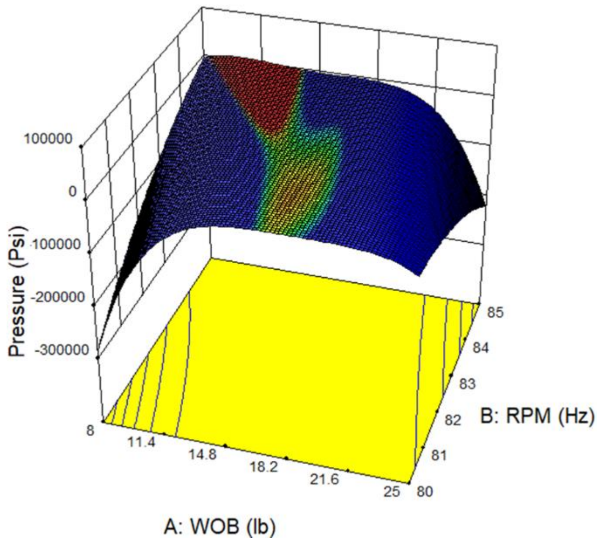

Figure 7. Effect of WOB and RPM on pressure

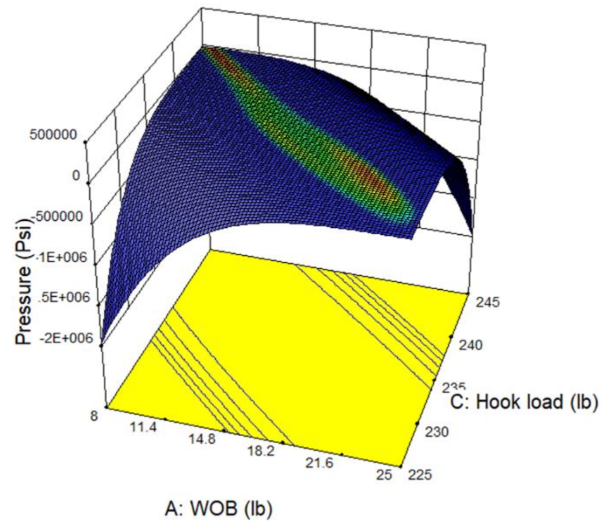

Figure 8. Effect of WOB and hook load on pressure

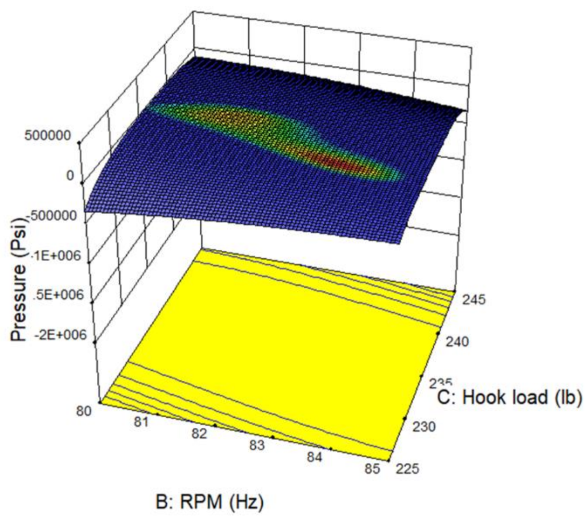

Figure 9. Effect of RPM and hook load on pressure

The effect of RPM and hook load on pressure is shown in Figure 9. It can be observed that the optimal region lies at intermediate values of the hook load (235 – 240 lb). Intermediate values of hook load give a good response for the pressure during the drilling process across the diverse strata of the conventional formation and hence, fully account for an increase because the intermediate values are sufficient to surge the pressure. In this domain, RPM had a minimal interactive effect with hook load as it affects the pressure.

4. Conclusion

In this study, RSM was used to model the effect of weight on bit (WOB), hook load and revolutions per minute (RPM) on the rate of penetration (ROP), pressure and torque. The models for all three responses were statistically significant (at a significance level of $p < 0.05$). ROP was observed to the optimum at low RPM (80 – 81 Hz) and high WOB (20 – 25 lb) and high RPM (83 – 85 Hz) and low WOB (8 – 14 lb). At low RPM (80 – 81 Hz) and an intermediate hook load (235 – 240 lb), ROP was observed to be high. It was observed that the torque is optimal anywhere above a hook load of 235 lb. In line with this, optimal drilling torque can only be achieved at an accelerated hook load resident at above 235 lbs and beyond given the pre-defined reservoir data set, because the two variables are simply reliant on the forward nature of the other. The pressure was highest at high RPM (83 – 85 Hz) and low WOB (8 – 12 lb). From this study, the effects of process factors on drilling parameters have been successfully modelled and investigated.

Disclosure statement

Conflict of Interest: The authors declare that there are no conflicts of interest. Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

Apendix

ANOVA table for ROP

ANOVA for Response Surface Sixth model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	44147.86	83	531.90	1.92	< 0.0001	significant
A-WOB	*402.62*	*1*	*402.62*	*1.46*	*0.2279*	
B-RPM	*34.41*	*1*	*34.41*	*0.12*	*0.7243*	
C-Hook load	*319.77*	*1*	*319.77*	*1.16*	*0.2825*	
AB	*20.68*	*1*	*20.68*	*0.075*	*0.7846*	
AC	*1.03*	*1*	*1.03*	*3.731E-003*	*0.9513*	
BC	*0.010*	*1*	*0.010*	*3.637E-005*	*0.9952*	
A^2	*2.90*	*1*	*2.90*	*0.010*	*0.9185*	
B^2	*380.53*	*1*	*380.53*	*1.38*	*0.2410*	
C^2	*0.21*	*1*	*0.21*	*7.634E-004*	*0.9780*	
ABC	*39.52*	*1*	*39.52*	*0.14*	*0.7055*	
A^2B	*47.77*	*1*	*47.77*	*0.17*	*0.6778*	
A^2C	*377.31*	*1*	*377.31*	*1.36*	*0.2430*	
AB^2	*18.01*	*1*	*18.01*	*0.065*	*0.7986*	
AC^2	*398.40*	*1*	*398.40*	*1.44*	*0.2303*	
B^2C	*1.96*	*1*	*1.96*	*7.087E-003*	*0.9329*	
BC^2	*32.27*	*1*	*32.27*	*0.12*	*0.7327*	
A^3	*369.79*	*1*	*369.79*	*1.34*	*0.2478*	
B^3	*5.62*	*1*	*5.62*	*0.020*	*0.8867*	
C^3	*429.01*	*1*	*429.01*	*1.55*	*0.2132*	
A^2B^2	*1.26*	*1*	*1.26*	*4.568E-003*	*0.9461*	
A^2BC	*51.80*	*1*	*51.80*	*0.19*	*0.6652*	
A^2C^2	*192.97*	*1*	*192.97*	*0.70*	*0.4037*	
AB^2C	*6.07*	*1*	*6.07*	*0.022*	*0.8822*	
ABC^2	*109.47*	*1*	*109.47*	*0.40*	*0.5294*	
B^2C^2	*25.92*	*1*	*25.92*	*0.094*	*0.7596*	
A^3B	*17.72*	*1*	*17.72*	*0.064*	*0.8002*	
A^3C	*163.48*	*1*	*163.48*	*0.59*	*0.4421*	
AB^3	*47.10*	*1*	*47.10*	*0.17*	*0.6799*	
AC^3	*210.20*	*1*	*210.20*	*0.76*	*0.3835*	
B^3C	*16.00*	*1*	*16.00*	*0.058*	*0.8100*	
BC^3	*190.48*	*1*	*190.48*	*0.69*	*0.4067*	
A^4	*126.61*	*1*	*126.61*	*0.46*	*0.4988*	
B^4	*335.21*	*1*	*335.21*	*1.21*	*0.2711*	
C^4	*212.46*	*1*	*212.46*	*0.77*	*0.3809*	
A^2B^2C	*264.92*	*1*	*264.92*	*0.96*	*0.3279*	
A^2BC^2	*0.86*	*1*	*0.86*	*3.109E-003*	*0.9555*	
AB^2C^2	*105.83*	*1*	*105.83*	*0.38*	*0.5363*	
A^3B^2	*463.08*	*1*	*463.08*	*1.67*	*0.1959*	
A^3BC	*4.56*	*1*	*4.56*	*0.016*	*0.8979*	
A^3C^2	*243.67*	*1*	*243.67*	*0.88*	*0.3481*	

ANOVA for Response Surface Sixth model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	44147.86	83	531.90	1.92	< 0.0001	significant
A^2B^3	697.09	1	697.09	2.52	0.1127	
A^2C^3	253.50	1	253.50	0.92	0.3386	
AB^3C	697.75	1	697.75	2.52	0.1125	
ABC^3	0.32	1	0.32	1.175E-003	0.9727	
B^3C^2	662.54	1	662.54	2.40	0.1220	
B^2C^3	19.18	1	19.18	0.069	0.7923	
A^4B	17.48	1	17.48	0.063	0.8015	
A^4C	248.65	1	248.65	0.90	0.3432	
AB^4	542.51	1	542.51	1.96	0.1616	
AC^4	278.90	1	278.90	1.01	0.3155	
B^4C	536.40	1	536.40	1.94	0.1640	
BC^4	0.97	1	0.97	3.498E-003	0.9528	
A^5	268.93	1	268.93	0.97	0.3243	
B^5	930.22	1	930.22	3.36	0.0669	
C^5	321.29	1	321.29	1.16	0.2813	
$A^2B^2C^2$	473.78	1	473.78	1.71	0.1909	
A^3B^3	403.06	1	403.06	1.46	0.2276	
A^3B^2C	417.34	1	417.34	1.51	0.2195	
A^3BC^2	633.34	1	633.34	2.29	0.1305	
A^3C^3	359.84	1	359.84	1.30	0.2542	
A^2B^3C	404.02	1	404.02	1.46	0.2270	
A^2BC^3	644.44	1	644.44	2.33	0.1272	
AB^3C^2	404.28	1	404.28	1.46	0.2269	
AB^2C^3	513.67	1	513.67	1.86	0.1732	
B^3C^3	403.67	1	403.67	1.46	0.2272	
A^4B^2	354.52	1	354.52	1.28	0.2578	
A^4BC	606.91	1	606.91	2.20	0.1388	
A^4C^2	312.01	1	312.01	1.13	0.2884	
A^2B^4	936.22	1	936.22	3.39	0.0661	
A^2C^4	410.50	1	410.50	1.48	0.2234	
AB^4C	965.74	1	965.74	3.49	0.0620	
ABC^4	646.48	1	646.48	2.34	0.1266	
B^4C^2	961.33	1	961.33	3.48	0.0625	
B^2C^4	528.68	1	528.68	1.91	0.1671	
A^5B	561.52	1	561.52	2.03	0.1545	
A^5C	266.91	1	266.91	0.97	0.3261	
AB^5	1218.89	1	1218.89	4.41	0.0360	
AC^5	463.31	1	463.31	1.68	0.1958	
B^5C	1339.55	1	1339.55	4.84	0.0280	
BC^5	646.68	1	646.68	2.34	0.1265	
A^6	224.07	1	224.07	0.81	0.3682	
B^6	1310.48	1	1310.48	4.74	0.0297	
C^6	516.38	1	516.38	1.87	0.1721	

ANOVA for Response Surface Sixth model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	44147.86	83	531.90	1.92	< 0.0001	significant
Residual	2.533E+005	916	276.49			
Lack of Fit	*2.530E+005*	*912*	*277.37*	*3.69*	*0.1031*	
Pure Error	*300.39*	*4*	*75.10*			
Cor Total	2.974E+005	999				

ANOVA table for torque

ANOVA for Response Surface Fifth model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	9.156E+007	55	1.665E+006	300.16	< 0.0001	significant
A-WOB	*4413.79*	*1*	*4413.79*	*0.80*	*0.3726*	
B-RPM	*2.288E+005*	*1*	*2.288E+005*	*41.26*	*< 0.0001*	
C-Hook load	*2717.04*	*1*	*2717.04*	*0.49*	*0.4841*	
AB	*6895.63*	*1*	*6895.63*	*1.24*	*0.2651*	
AC	*23263.34*	*1*	*23263.34*	*4.19*	*0.0408*	
BC	*3253.36*	*1*	*3253.36*	*0.59*	*0.4439*	
A^2	*15580.77*	*1*	*15580.77*	*2.81*	*0.0940*	
B^2	*45548.26*	*1*	*45548.26*	*8.21*	*0.0043*	
C^2	*29451.64*	*1*	*29451.64*	*5.31*	*0.0214*	
ABC	*11177.77*	*1*	*11177.77*	*2.02*	*0.1560*	
A^2B	*8162.82*	*1*	*8162.82*	*1.47*	*0.2254*	
A^2C	*43489.58*	*1*	*43489.58*	*7.84*	*0.0052*	
AB^2	*401.58*	*1*	*401.58*	*0.072*	*0.7879*	
AC^2	*42780.44*	*1*	*42780.44*	*7.71*	*0.0056*	
B^2C	*171.37*	*1*	*171.37*	*0.031*	*0.8605*	
BC^2	*15000.18*	*1*	*15000.18*	*2.70*	*0.1004*	
A^3	*41887.25*	*1*	*41887.25*	*7.55*	*0.0061*	
B^3	*12874.67*	*1*	*12874.67*	*2.32*	*0.1279*	
C^3	*39926.85*	*1*	*39926.85*	*7.20*	*0.0074*	
A^2B^2	*12217.17*	*1*	*12217.17*	*2.20*	*0.1381*	
A^2BC	*616.97*	*1*	*616.97*	*0.11*	*0.7388*	
A^2C^2	*9535.39*	*1*	*9535.39*	*1.72*	*0.1901*	
AB^2C	*13253.81*	*1*	*13253.81*	*2.39*	*0.1225*	
ABC^2	*143.68*	*1*	*143.68*	*0.026*	*0.8722*	
B^2C^2	*13914.36*	*1*	*13914.36*	*2.51*	*0.1135*	
A^3B	*1610.34*	*1*	*1610.34*	*0.29*	*0.5901*	
A^3C	*7833.75*	*1*	*7833.75*	*1.41*	*0.2349*	
AB^3	*26.58*	*1*	*26.58*	*4.792E-003*	*0.9448*	
AC^3	*11006.96*	*1*	*11006.96*	*1.98*	*0.1592*	
B^3C	*1037.65*	*1*	*1037.65*	*0.19*	*0.6654*	
BC^3	*3.48*	*1*	*3.48*	*6.268E-004*	*0.9800*	
A^4	*5940.03*	*1*	*5940.03*	*1.07*	*0.3010*	

ANOVA for Response Surface Fifth model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
B^4	13807.79	1	13807.79	2.49	0.1149	
C^4	12145.10	1	12145.10	2.19	0.1393	
A^2B^2C	22557.69	1	22557.69	4.07	0.0440	
A^2BC^2	17171.73	1	17171.73	3.10	0.0788	
AB^2C^2	20625.16	1	20625.16	3.72	0.0541	
A^3B^2	23809.92	1	23809.92	4.29	0.0385	
A^3BC	19370.90	1	19370.90	3.49	0.0619	
A^3C^2	28630.02	1	28630.02	5.16	0.0233	
A^2B^3	14309.31	1	14309.31	2.58	0.1085	
A^2C^3	29451.54	1	29451.54	5.31	0.0214	
AB^3C	13588.14	1	13588.14	2.45	0.1179	
ABC^3	15073.13	1	15073.13	2.72	0.0996	
B^3C^2	12228.13	1	12228.13	2.20	0.1379	
B^2C^3	18060.33	1	18060.33	3.26	0.0715	
A^4B	21463.10	1	21463.10	3.87	0.0494	
A^4C	28194.01	1	28194.01	5.08	0.0244	
AB^4	6295.47	1	6295.47	1.14	0.2870	
AC^4	30652.84	1	30652.84	5.53	0.0189	
B^4C	3430.41	1	3430.41	0.62	0.4318	
BC^4	13273.46	1	13273.46	2.39	0.1222	
A^5	28073.01	1	28073.01	5.06	0.0247	
B^5	15095.47	1	15095.47	2.72	0.0993	
C^5	32121.86	1	32121.86	5.79	0.0163	
Residual	5.235E+006	944	5546.00			
Lack of Fit	5.235E+006	940	5569.60			
Pure Error	0.000	4	0.000			
Cor Total	9.679E+007	999				

ANOVA table for pressure

ANOVA for Response Surface Quartic model						
Analysis of variance table [Partial sum of squares - Type III]						
Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1.505E+006	34	44274.67	20.40	< 0.0001	significant
A-WOB	3099.83	1	3099.83	1.43	0.2323	
B-RPM	63314.97	1	63314.97	29.18	< 0.0001	
C-Hook load	2880.47	1	2880.47	1.33	0.2496	
AB	102.34	1	102.34	0.047	0.8281	
AC	3004.72	1	3004.72	1.38	0.2396	
BC	1522.91	1	1522.91	0.70	0.4024	
A^2	4400.99	1	4400.99	2.03	0.1547	
B^2	2014.91	1	2014.91	0.93	0.3355	
C^2	2384.03	1	2384.03	1.10	0.2948	
ABC	1153.03	1	1153.03	0.53	0.4662	

A^2B	3410.79	1	3410.79	1.57	0.2103
A^2C	8.92	1	8.92	4.111E-003	0.9489
AB^2	1087.38	1	1087.38	0.50	0.4792
AC^2	102.73	1	102.73	0.047	0.8278
B^2C	7.39	1	7.39	3.404E-003	0.9535
BC^2	224.93	1	224.93	0.10	0.7476
A^3	86.44	1	86.44	0.040	0.8418
B^3	39.22	1	39.22	0.018	0.8931
C^3	160.88	1	160.88	0.074	0.7855
A^2B^2	929.94	1	929.94	0.43	0.5129
A^2BC	1025.96	1	1025.96	0.47	0.4919
A^2C^2	1204.93	1	1204.93	0.56	0.4564
AB^2C	918.62	1	918.62	0.42	0.5154
ABC^2	830.57	1	830.57	0.38	0.5363
B^2C^2	1190.28	1	1190.28	0.55	0.4591
A^3B	1367.92	1	1367.92	0.63	0.4274
A^3C	1235.85	1	1235.85	0.57	0.4506
AB^3	180.06	1	180.06	0.083	0.7734
AC^3	1218.37	1	1218.37	0.56	0.4539
B^3C	336.05	1	336.05	0.15	0.6940
BC^3	667.62	1	667.62	0.31	0.5793
A^4	1367.27	1	1367.27	0.63	0.4275
B^4	17.94	1	17.94	8.265E-003	0.9276
C^4	1240.76	1	1240.76	0.57	0.4497
Residual	2.094E+006	965	2170.04		
Lack of Fit	2.094E+006	961	2179.07		
Pure Error	0.000	4	0.000		
Cor Total	3.599E+006	999			

References

1. Chima CM. Supply-chain management issues in the oil and gas industry. Journal of Business & Economics Research (JBER). 2007; 5.
2. Mawell S. Microseismic imaging of hydraulic fracturing: Improved engineering of unconventional shale reservoirs. SEG Books, 2014.
3. Eren T and Ozbayoglu ME. Real time optimization of drilling parameters during drilling operations. SPE Oil and Gas India conference and exhibition. Society of Petroleum Engineers, 2010.
4. Egbe P and Iturrios C. Mitigating Drilling Hazards in a High Differential Pressure Well Using Managed Pressure Drilling and Cementing Techniques. International Petroleum Technology Conference. Dhahran, Kingdom of Saudi Arabia: International Petroleum Technology Conference, 2020, p. 13.
5. Abd Rahman AM. Optimization of weight on bit during drilling operation based on rate of penetration model. 2011.
6. Han J, Sun Y and Zhang S. A Data Driven Approach of ROP Prediction and Drilling Performance Estimation. International Petroleum Technology Conference. Beijing, China: International Petroleum Technology Conference, 2019, p. 9.
7. Nwabueze QA and Ighalo JO. Production and Economic Analysis of Enhanced Oil Recovery (EOR) by Water Flooding: A case study of Reservoir OB-48 In the Niger Delta Petroleum and Coal, 2020; 62: 103-13.
8. Khakzad N, Khan F and Amyotte P. Quantitative risk analysis of offshore drilling operations: A Bayesian approach. Safety science, 2013; 57: 108-17.
9. Ritto T, Soize C and Sampaio R. Robust optimization of the rate of penetration of a drill-string using a stochastic nonlinear dynamical model. Computational Mechanics, 2010; 45: 415-27.

10. Smith SA and Comeskey AE. Sustainable wells: maintenance, problem prevention, and rehabilitation. CRC Press, 2009.
11. Jain JR, Ricks G, Ledgerwood L and Phillips A. Mitigating Drilling Dysfunctions and Enhancing Performance with Self-Adjusting Bit Technology: Analytical and Experimental Case Studies. SPE/IADC Drilling Conference and Exhibition. Society of Petroleum Engineers, 2017.
12. Asghar Jafari A, Kazemi R and Faraji Mahyari M. The effects of drilling mud and weight bit on stability and vibration of a drill string. Journal of vibration and acoustics, 2012; 134.
13. Bourgoyne Jr AT and Young Jr F. A multiple regression approach to optimal drilling and abnormal pressure detection. Society of Petroleum Engineers Journal, 1974; 14: 371-84.
14. Jahanbakhshi R, Keshavarzi R and Jafarnezhad A. Real-time Prediction of Rate of Penetration During Drilling Operation In Oil And Gas Wells. 46th US Rock Mechanics/Geomechanics Symposium. Chicago, Illinois: American Rock Mechanics Association, 2012, p. 7.
15. Moraveji MK and Naderi M. Drilling rate of penetration prediction and optimization using response surface methodology and bat algorithm. Journal of Natural Gas Science and Engineering. 2016; 31: 829-41.
16. Cheatham CA and Nahm JJ. Effects of Selected Mud Properties on Rate of Penetration in Full-Scale Shale Drilling Simulations. SPE/IADC Drilling Conference. New Orleans, Louisiana: Society of Petroleum Engineers, 1985, p. 9.
17. Khuri AI and Mukhopadhyay S. Response surface methodology. Wiley Interdisciplinary Reviews: Computational Statistics, 2010; 2: 128-49.
18. Hill WJ and Hunter WG. A review of response surface methodology: a literature survey. Technometrics, 1966; 8: 571-90.
19. Ighalo JO and Adeniyi AG. Factor effects and interactions in steam reforming of biomass bio-oil. Chemical Papers, 2019; 74: 1459-70.
20. Adeniyi AG, Ighalo JO and Odetoye TE. Response surface modelling and optimisation of biodiesel production from Avocado plant (*Persea americana*) oil. Indian Chemical Engineer, 2020; 62(3): 243-250.
21. Kasim MS. Comparison between Taguchi method and response surface methodology (RSM) in optimizing machining condition. Proceeding of 1st International Conference on Robust Quality Engineering. 2013, p. 60-8.
22. Widyaningsih T, Widjanarko S, Waziiroh E, Wijayanti N and Maslukhah Y. Pilot plant scale extraction of black cincau (Mesona palustris BL) using historical-data response surface methodology. International Food Research Journal, 2018; 25.
23. Mahmoodi NM, Keshavarzi S and Rezaei P. Synthesis of copper oxide nanoparticle and photocatalytic dye degradation study using response surface methodology (RSM) and genetic algorithm (GA). Desalination and Water Treatment, 2017; 72: 394-405.
24. Zhao Y, Noorbakhsh A, Koopialipoor M, Azizi A and Tahir M. A new methodology for optimization and prediction of rate of penetration during drilling operations. Engineering with Computers, 2019: 1-9.
25. Al-AbdulJabbar A, Elkatatny S, Abdulhamid Mahmoud A, et al. Prediction of the Rate Penetration while Drilling Horizontal Carbonate Reservoirs Using a Self-Adaptive Artificial Neural Network Technique. Sustainability, 2020; 12: 1376.
26. Alum MA and Egbon F. Semi-Analytical Models on the Effect of Drilling Fluid Properties on Rate of Penetration (ROP). Nigeria Annual International Conference and Exhibition. Abuja, Nigeria: Society of Petroleum Engineers, 2011, p. 13.
27. Schamp JH, Estes BL and Keller SR. Torque Reduction Techniques in ERD Wells. IADC/SPE Drilling Conference. Miami, Florida, USA: Society of Petroleum Engineers, 2006, p. 9.
28. van Riet EJ, Reitsma D and Vandecraen B. Development and Testing of a Fully Automated System to Accurately Control Downhole Pressure During Drilling Operations. SPE/IADC Middle East Drilling Technology Conference and Exhibition. Abu Dhabi, United Arab Emirates: Society of Petroleum Engineers, 2003, p. 12.

To whom correspondence should be addressed: Joshua O. Ighalo, Department of Chemical Engineering, Nnamdi Azikiwe University, P. M. B. 5025, Awka, Nigeria, E-mail: oshea.ighalo@yahoo.com