IMPROVED MODEL FOR DRILLING RATE OF PENETRATION (ROP)

Ayodele Ajayi and Kelani Bello

Department of Petroleum Engineering,
University of Benin, Benin City, Nigeria.

Abstract
No single parameter can adequately describe how well a drilling operation has been accomplished. This is often the case during drilling optimization processes. The inability of existing Rate of penetration models to accurately predict ROP was considered. The existing models have been based on assumptions of perfect hole cleaning conditions thus under-describing the actual severity of the situation for an accurate solution.

A new model has been developed which took account of deficiencies of existing models based on key drilling parameters such as weight on bit, rotary speed, formation drillability and tooth wear in order to mimic actual drilling condition. The simulated drilling rate were compared with that obtained from existing models in the literatures and analyzed using an excel worksheet.

The model predicted the field data with average error margin of 6.3%. This was a significant improvement when compared with existing models in the literatures. The improved model was validated using an independent field data and were shown to have better predictions when compared with existing models in public domain

Introduction
The purpose of Drilling optimization is to achieve maximum drilling efficiency and minimum expenditure through logical process of analyzing the effect and interactions of drilling variables by mathematical models.

In recent years, drilling of wells has shown considerable technological advancements which have helped reduce uncertainties associated with many drilling. This may have contributed significantly to a safe, environmental friendly and cost effective Well construction.

Major drilling variables considered to have effects on drilling rate of penetration are not fully understood and are indeed complex to model. These challenges led to the development of a simple but fit for purpose model for rate of penetration that has better predictive capability when compared with existing models in public domain. There are many proposed mathematical models (Analytical and Numerical) which attempt to combine known relations of drilling parameters to model rate of penetration, few of which are discussed below;

Bourgoyne and Young; constructed a linear penetration rate model and performed a multiple regression analysis of drilling data. In their analysis, the effects of formation strength, formation depth, formation compaction, pressure differential across the hole bottom, bit diameter, bit weight, rotary speed, bit wear and bit hydraulics on rate of penetration were observed. The equation proposed by Bourgoyne and young is expressed as

$$\frac{dF}{dt} = e(a1 + \sum_{j=2}^{8}(\text{aj xj}) \quad (1)$$

Bingham proposed a rate of penetration equation based on laboratory data. The equation threshold assumed bit weight to be negligible and rate of penetration was a function of applied weight on the bit and rotary speed of the string. The bit weight exponent, d was set to be determined experimentally through the prevailing conditions.

$$\frac{dF}{dt} = \boldsymbol{K}\left(\frac{W}{d_b}\right)^{d} \boldsymbol{N^e} \quad (2)$$

Galle and Woods; are one of the first researchers who investigated the effect of constant bit weight and rotary speed for lowest drilling cost. They developed mathematical relations, which included graphs and procedures for field applications in order to determine best combinations of constant weight and rotary speed. The drilling costs were demonstrated to be reduced using the recommended combinations of the drilling parameters. They expressed drilling rate as a function of WOB and RPM.

$$\frac{dF}{dt} = C_{fd}\frac{W^{\alpha}N^{\beta}}{a^{p}} \quad (3)$$

This study work with numerical and analytical models to observe the effects of drilling parameters on the rate of penetration, after which the best correlation is use to maximize the ROP during drilling operations.

Model Development

Galle and wood proposed the equation below to model drilling rate.

$$\frac{dF}{dt} = C_{fd}\frac{W^{\alpha}N^{\beta}}{a^{p}} \quad (3)$$

Correlation coefficient called formation drillability

$0.6 \leq \alpha \leq 2.0$

$0.4 \leq \beta \leq 1.0$

$p = 1.0$ *For flat tooth wear (non-sharpening)*

$p = 0.5$ *For self-sharpening*

Given rate of tooth wear, we have;

$$\frac{dh}{dt} = \frac{1}{A}\frac{i}{am} \quad (4)$$

$$i = N + 4.348 * 10^{-5}N^3 \quad (5)$$

$$a = 1 + 6h + 0.928h^2 \quad (6)$$

$$\int a dh = h + 3h^2 + 0.309h^3 \quad (7)$$

$$\int a^{1-p} dh = -0.0067 + 1.15h + 0.871h^2 \quad (8)$$

$$m = 1359.1 - 714.19\log_{10} W' \quad (9)$$

$$W' = W * \frac{7.875}{d_b} \quad (10)$$

A= correlation coefficient for tooth wear called formation abrasiveness factor
W'= Equivalent weight
W= Actual weight on bit

For the rate of bearing wear we have

$$\frac{dB}{dt} = \frac{1}{S}\frac{N}{L} \quad (11)$$

Given that

$$B = \frac{N}{SL} * RT \quad (12)$$

$$L = e^{8.9609 + 0.90393 Ln W' - 0.36297 (Ln W')^2} \quad (13)$$

Where
S= Correlation coefficient called drilling fluid factor
B= Fraction of bearing life consumed
Integrating Eqn. (4) gives the bit rotation life (time)

$$RT = a\frac{m}{i}\int a dh \quad (14)$$

Substituting Eqn. (14) into Eqn. (12) gives the bearing wear in terms of tooth dullness

$$B = \frac{N}{SL} * a\frac{m}{i}\int a dh \quad (15)$$

Bit footage is

$$F = \frac{dF}{dT}dT = C_f W^{\alpha} N^{\beta} a \frac{m}{i} \int adh \quad (16)$$

Re-arranging Eqn. (16) to make C_f the Subject of the formula, we have

$$C_f = \frac{F}{W^{\alpha} N^{\beta} a \frac{m}{i} \int adh} \quad (17)$$

the Subject of the formula, we have

$$a = \frac{RT}{a \frac{m}{i} \int adh} \quad (18)$$

Substituting Eqn. (18) into Eqn. (17) we have

$$C_f = \frac{F}{W^{\alpha} N^{\beta} \left(\frac{RT}{a \frac{m}{i} \int adh}\right) \frac{m}{i} \int adh}$$

This simplifies to

$$C_f = \frac{F/RT}{W^{\alpha} N^{\beta} \frac{\int a^{1-p} dh}{\int adh}} \quad (19)$$

Combining Eqn. (3) with Eqn. (19) we have

$$\frac{dF}{dT} = \frac{F/RT}{W^{\alpha} N^{\beta} \frac{\int a^{1-p} dh}{\int adh}} \frac{W^{\alpha} N^{\beta}}{a^{p}}$$

This simplifies to give the equation below

$$\frac{dF}{dT} = \frac{F/RT}{a^{p}} \frac{\int adh}{\int a^{1-p} dh} \quad (20)$$

Where F/RT is the actual drilling rate while $\frac{dF}{dT}$ is our predicted ROP

Thus Equation (20) is now our new model for predicting ROP; hence it is named modified Galle and Wood model and are defined by Equations 6, 7, and 8.

In the section below, the ROP model developed would be compared with existing models (Bingham and Bourgoyne & Young model) to test for its validity and accuracy in predicting Rate of Penetration.

Results & Analysis

Using the field data obtained from Kinabalu East-1, 1990. The various figures showing predicted Rate of Penetration and Actual drilling rate vs. Depth, are given below

The ROP model that simulates the Actual drilling rate with the highest degree of accuracy is the MODIFIED GALLE and WOOD model, followed by BOURGOYNE and YOUNG model and lastly BINGHAM model. BOURGOYNE and YOUNG model mimics the drilling rate better as it considers more drilling parameters in its analysis.

Sensitivity analysis was carried out to eliminate spurious data to improve on the accuracy of the models.

Table 1: Field data from Kinabalu East-1, 1990
(Sabah Shell Petroleum Company Limited)

Data Entry	Depth, ft	Bit Number	Drilling Rate, ft/hr	Bit Weight(1000lb/1n.)	Rotary Speed, rpm	Tooth Wear	Reynolds Number Function	ECD, lb/gal	Pore Gradient, ppg
1	9515	7	23	2.58	113	0.77	0.964	9.5	9
2	9830	8	22	1.15	126	0.38	0.964	9.5	9
3	10130	9	14	0.81	129	0.74	0.827	9.6	9
4	10250	11	10	0.95	87	0.15	0.976	9.7	9
5	10390	12	16	1.02	78	0.24	0.984	9.7	9
6	10500		19	1.69	81	0.61	0.984	9.7	9.1
7	10575		13	1.56	81	0.73	0.984	9.7	9.2
8	10840	13	16.6	1.63	67	0.38	0.932	9.8	9.3
9	10960		15.9	1.83	65	0.57	0.878	9.8	9.4
10	11060		15.7	2.03	69	0.72	0.878	9.8	9.5
11	11475	15	14	1.69	77	0.2	0.887	10.3	9.5
12	11775	18	13.5	2.31	58	0.12	0.852	11.8	10.1
13	11940	21	6.2	2.26	67	0.2	0.976	15.3	12.4
14	12070	22	9.6	2.07	84	0.08	0.993	15.7	13
15	12315		15.5	3.11	69	0.4	1.185	16.3	14.4
16	12900	23	31.4	2.82	85	0.42	1.15	16.7	15.9
17	12975	24	42.7	3.48	77	0.17	1.221	16.7	16.1
18	13055		38.6	3.29	75	0.29	1.161	16.8	16.2
19	13250		43.4	2.82	76	0.43	1.161	16.8	16.2
20	13795	25	12.5	1.6	81	0.56	0.272	16.8	16.2
21	14010	26	21.1	1.04	75	0.46	0.201	16.8	16.2
22	14455	28	19	1.76	64	0.16	0.748	16.9	16.2
23	14695		18.7	2	76	0.27	0.819	17.1	16.2
24	14905	29	20.2	2.35	75	0.33	0.419	17.2	16.4
25	15350	30	27.1	2.12	85	0.31	1.29	17	16.5
26	15740		14.8	2.35	78	0.81	0.802	17.3	16.5
27	16155	32	12.6	2.47	80	0.12	0.67	17.9	16.5
28	16325		14.9	3.76	81	0.5	0.532	17.5	16.6
29	17060	34	13.8	3.76	65	0.91	0.748	17.6	16.6
30	20265	40	9	3.4	60	0.01	0.512	17.7	16

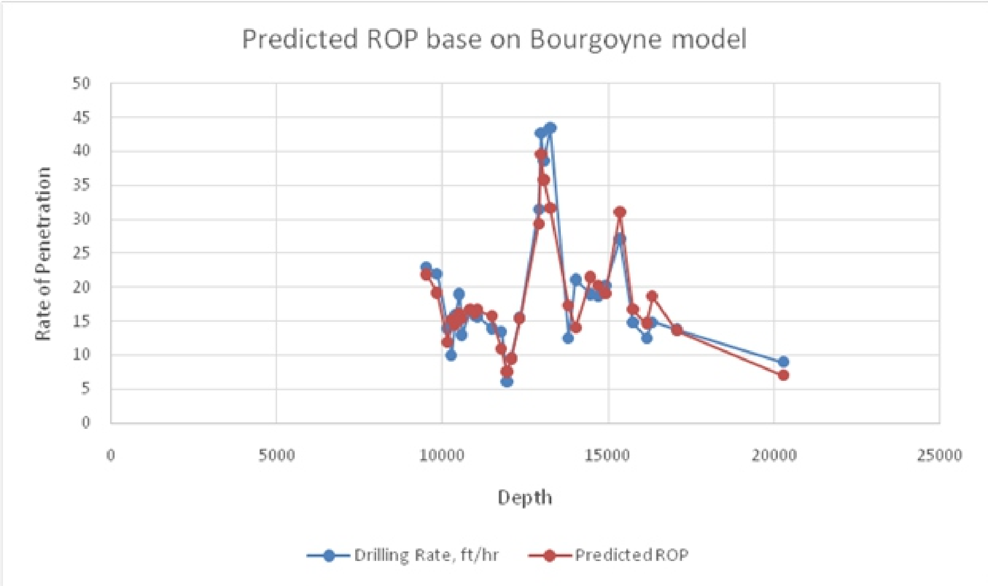

Figure 1: Predicted ROP and Actual drilling rate vs. Depth (Bourgoyne and Young model)

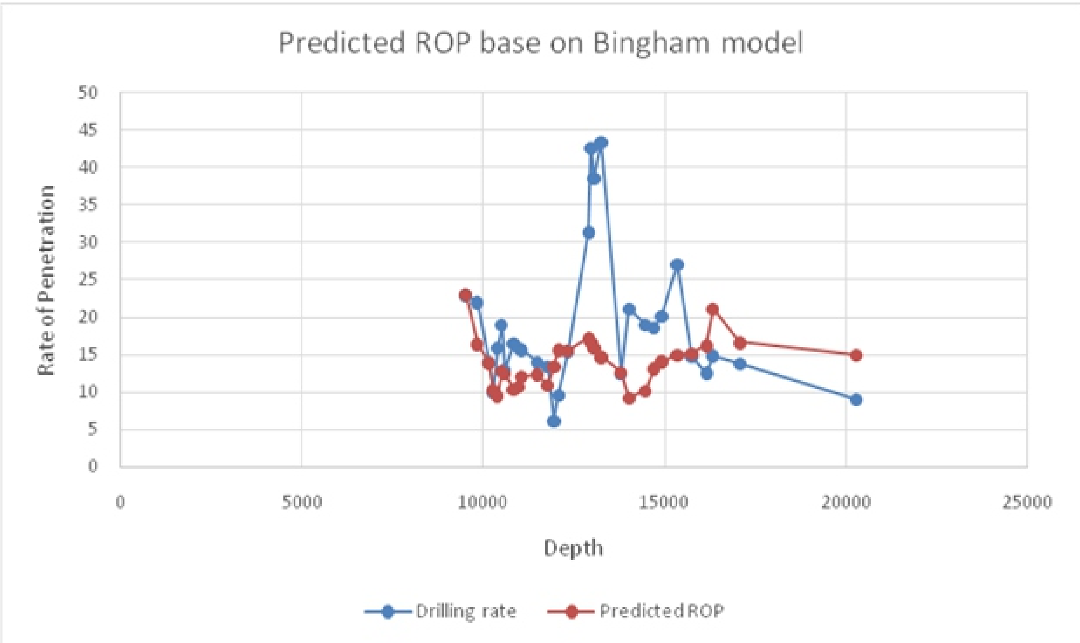

Figure 2: Predicted ROP and Actual drilling rate vs. Depth (Bingham model)

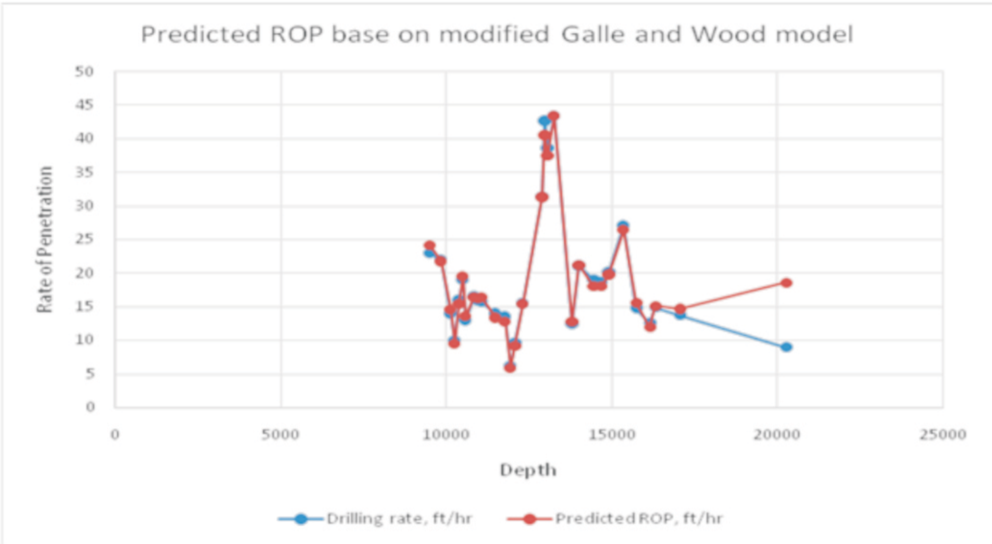

Figure 3: Predicted ROP and Actual drilling rate vs. Depth (Modified Galle and Wood)

Sensitivity analysis carried out obtained the figures below for the three models.

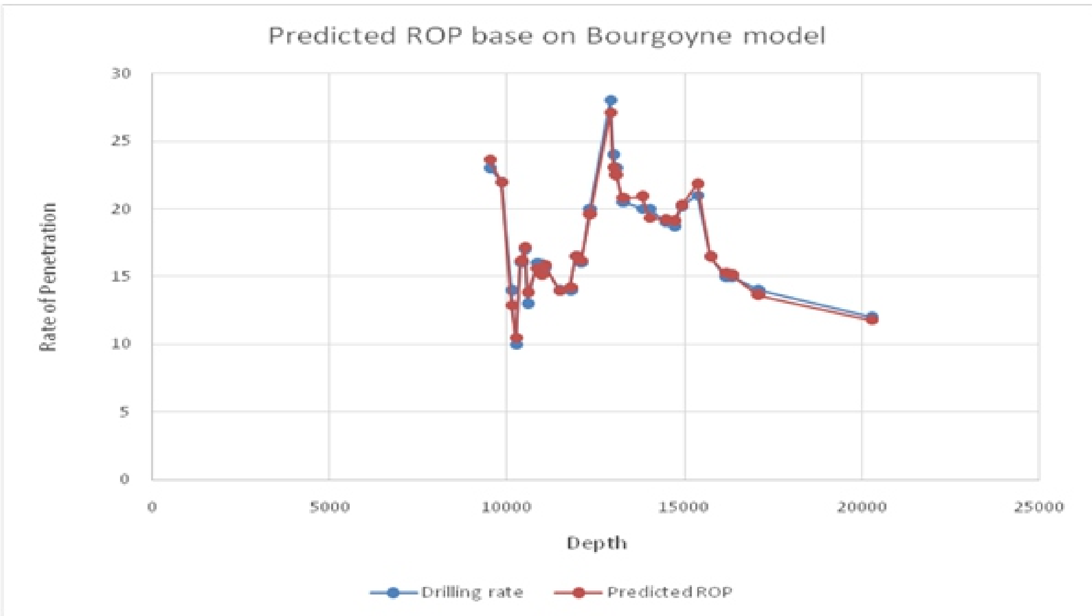

Figure 4; Predicted ROP and Actual drilling rate vs. Depth (Bourgoyne and Young)

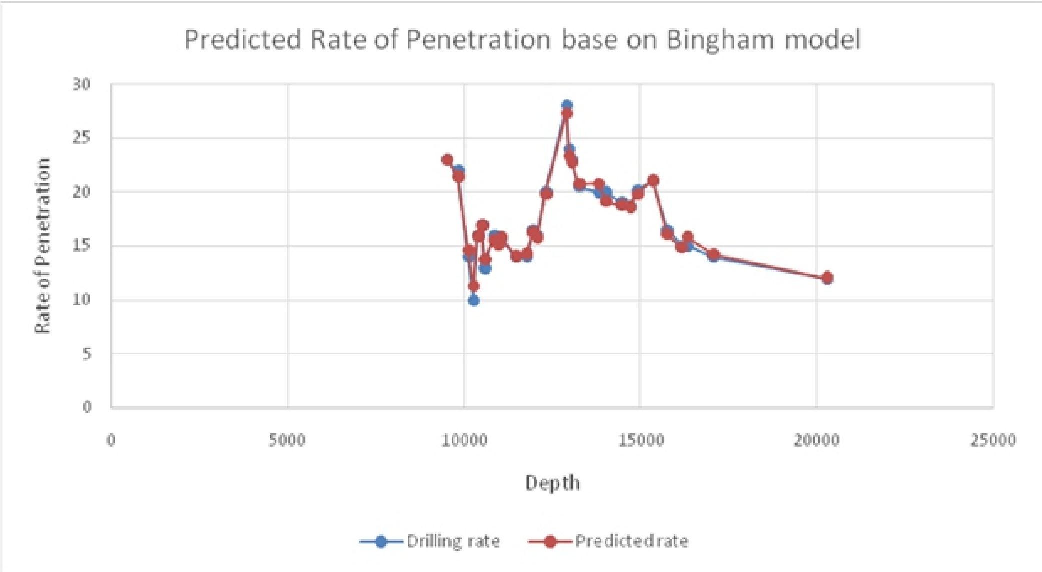

Figure 5; Predicted ROP and Actual drilling rate vs. Depth (Bingham)

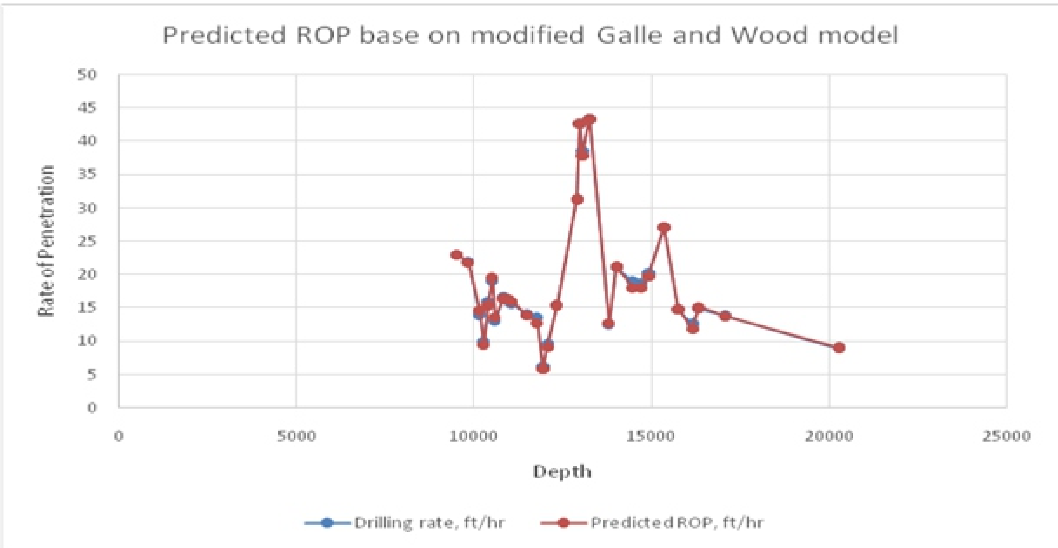

Figure 6; Predicted ROP and Actual drilling rate vs. Depth (Modified Galle and Wood)

A number of drilling parameters were analyzed to identify the performance of a drilling operation. On rare occasions has a single parameter adequately describe how well a drilling operation has been accomplished. From the results and the various plots, there is a close agreement between the Actual drilling rate and the predicted values for the Rate of Penetration obtained from the data on which sensitivity analysis has been carried out. The simplicity at which the new method can be derived and applied to analytically evaluate Rate of penetration accurately makes it a better tool.

Table 2: Comparison of S-values

MODELS	P-values(prior to S.A.)	P-values(after S.A.)
Bourgoyne and Young model	356.5828159	8.255318732
Bingham model	3035.689314	7.365266579
Modified Galle & Wood Model	106.6306143	5.27067

P-value is the sum of squares of the deviation between the predicted Rate of Penetration and the Actual drilling rate. It is a measure of best fit.

The accuracy of the three models in predicting the ROP based on the P-values, the MODIFIED GALLE and WOOD MODEL is a better tool for simulating the Actual drilling rate. But all of these models found application in evaluating the economic feasibility and enhancing the development plan of a particular area in order to help accomplish effective drilling operations at the least possible cost.

Conclusion

As more wells are drilled around the world daily, it becomes necessary to carry out research and development in order to describe optimization of drilling parameters as well as the factors that may affect it. This work have been able to establish that drilling rate of penetration (ROP) can be predicted using offset field data using a simple analytical method as against complex mathematical procedures requiring drilling parameters that are not readily available. This new model has therefore provided a better predictive tool with simple to use procedures when compared with other models in the literatures.

The results of this model can be used by drilling engineers to make informed decision on right combination of Weight on bit (WOB) and Rotary speed (RS) during a drilling operation or in the development plan of an unexplored area.

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