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Meta-Analysis of Penetration Rate by Using Empirical Correlations

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ABSTRACT

The rate of penetration (ROP) is one of the most important factors in improving drilling efficiency, is a measure of the speed or the progress of the drill bit when it drills subsurface formation. The study will be conducted with the input data sets of ROP, WOB, RPM, and all drilling data provided. To maximize the accuracy. In this paper, i collected data related to the rate of penetration from three wells in three different fields in Libya, and these fields are (Al-Sarir "the largest field in North Africa" - Amal field - Al-Sharara field). In the second stage, we will build an ROP model to compare the results of the rate of penetration in each well and each field. Finally, we make a recommendation on the best equation for each field, which gives results that are close to reality To be used to predict the rate of penetration in the future.

INTRODUCTION

In recent years the increasing demand for energy research from the ground has forced operators to develop a subject of survey ensuring that well drilling is realized in a more efficient manner. For that reason oil and gas companies tend to find different methods with different consideration on drilling activities in order to reduce cost, increase performance and overcome possible difficulties. There is no doubt that energy sources are reducing day by day and the oilfield exploitation will be more difficult in the future. These entail that the future project should improve productivity and make well construction cost effective. (R. F. Mitchell, 2011)

The rate of penetration (ROP) is the speed at which the drill bit can break the rock under it and thus deepen the wellbore. This speed is usually reported in units of feets per hour or meters per hour.(R. F. Mitchell, 2011)

The factors which affect rate of penetration are exceedingly numerous but these parameters Weigth on bit (WOB), Rotation per minute (RPM), Flow rate (FR) and Mud weight (MW) are the most important for rate of penetration deciding

In order to drill a well, three factors have to be established together. First of all, a certain load has to be applied on the bit, and this is known as the weight on the drill string against the hole being drilled. The drillstring rotation speed by the rig rotary equipment, such as the top drive or the kelly in older rigs, is measured in revolutions per minute (RPM). The action of WOB and drillstring rotation generates a torque (T) as a result of the interaction between the drilling bit and the drilled formation in addition to friction with the wellbore wall bit (WOB). WOB can be achieved by the rig hoisting system by slacking some weight of (He X. et al. 1995)

The meta-analysis uses statistical methods on the results of several previous studies in order to identify a tendency or tendency to those results or to find a possible interrelationship between them.(Greenland S, O. 2008)

Meta-analysis improves the accuracy and proximity of results to our estimates as we increase the amount of data used. This, in turn, can increase the statistical power to detect any effect.(Greenland S, O. 2008)

Any inconsistency in studies can be quantified and analyzed as well, and hypothesis testing can be applied to summary estimates and estimations.

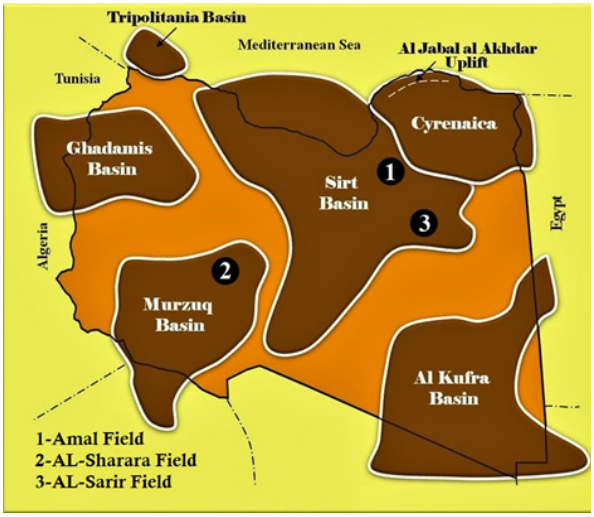

Figure 1: Position of Libyan fields that used in our study

Objectives

This study aims to achieve this goals

1. Understand the ROP property and its related properties
2. Provide a recommendation on choosing and adopting the closest equation to the real data in each field
3. Save time and reduce the cost

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4. predict of ROP useful for projects management to design drilling well

5. Knowing the appropriate equation closest to reality in each field to predict the penetration rate

METHODOLOGY

In this study, I selected a three of the most famous fields in Libya, and the data of three different wells were taken from each field to use empirical correlations, so that the results are more accurate. I built an Excel model to analyze data and solve ROB model equations.

This study will be conducted with the ROP modeling (Maurer, Bingham, ,Warren, Galle and Wood, Bourgoyne and Young models.) Models To provide more accuracy

ROP Modeling

there are many ROP models have been developed in the last decade as we mentioned in the previous section. In this paper, we used Five Models: (Maurer, Bingham, Warren, G&W, and B&Y models.)

The percentage error at each selected depth was calculated using formula

Average Error Percentage = [(Predicted ROP – Actual ROP) / Actual ROP)] * 100

Maurer's Method 1962

Based on the ideal principle of cleaning of rotary drilling, Maurer established a boil rate of penetration in 1962. Maurer developed penetration rate of bits of the roller-cone given the process of the rock cratering. The calculation was based on the state of "complete brushing" where all rock dust is deemed extracted between the impact of the tooth. A working relationship was established between drilling intensity, bit weight and string speed given that the hole was properly cleaned under conditions. The relationships acquired were also noted as depending on the extent of perforation (W. Maurer, 1962). The intensity of the boiling equation as shown below

$$ROP = \mathrm{K} \times \frac{\mathrm{RPM} \times WOB^2}{\mathrm{Db}^2 \times \mathrm{UCS}^2}$$

Where,

ROP = Rate of penetration (ft/hr)

K = Constant of proportionality

RPM = Rotary Speed

WOB = Weight on bit (klbf)

Db = Bit diameter (inch)

UCS = Rock strength (psi)

Bingham's Method 1965

Bingham's 1965 paper suggested a model that predicted ROP by considering it as simply function of rotary speed, weight on bit, and bit diameter; however, it is known to be limited tolow WOB, and RPM (Bingham G. 1965)

Bingham's equation is as follows:

$ROP = \propto \times RPM \times (WOB/Db)^{\beta}$

Where,

ROP = Rate of penetration (ft/hr)

RPM = Rotary Speed

WOB = Weight on bit (klbf).

Db = Bit diameter (inch)

α and β are constants determined for a given rock formation.

Warren's Method 1981

Warren's model attempts to reflect on the shortcomings of the previous ones and to take into account what they did not. Due to the complexity and the number of factors that affect the penetration of the bit and its rate, the model that warren proposed is one that uses tests and data from research drilling rigs and takes into account the weight on bit (WOB), the rotary speed, hydraulic capacity and torque.(T. M. Warren. 1981)

$$ROP = \left(\frac{aS^2 d_b^3}{N^b WOB^2} + \frac{c}{Nd_b} + \frac{cdb\gamma f\mu}{Fjm}\right)^{-1}$$

Where:

S = the rock strength (psi)

db = bit diameter (inch)

N = rotary speed

WOB = weight on bit (klbf).

γf = Drilling fluid density

μ = Drilling fluid plastic viscosity (cp)

a , b , c = dimensionless bit constants

Fjm = Modified jet impact force function (klbf)

Galle & Woods' Method, 1963

pattern for rotary rock parts. The weight selection impact on bit WOB and RPM has been examined. You provided the best selection diagrams of the mixture of boiling parameters. They have shown that when utilizing their system, boxing costs are reduced. We have also published In 1963 Galle and Woods introduced the best perforated weight and spinning speed (Galle E.M and Woods A.B. 1963)

$$ROP = C_{fd} \times \frac{W^k r}{a^p}$$

$$r_{\text{Hard-formatio}} = \left(e^{\frac{-100}{N^2}} N^{-0.428} + 0.2N\left(1 - e^{\frac{-100}{N^2}}\right)\right)$$

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

Where

a = 0.028125 h2 + 6.0h + 1

W = 7.88WOB/D_b

k = 1.0

p = 0.5

N = rotary speed

Cfd is the formation drill ability parameter

Bourgoyne and Young's' Method, 1974

In 1974, Bourgoyne and Young introduced a concept for the penetration of boiling levels when the optimum boiling and irregular measurement of pressure using a multi-regression method. The process of boiling optimization is the largest approach for Bourgoyne and youngsters. This approach is therefore deemed the most suitable tool for maximizing drilling in real time. Data of

at least 25 wells were used to extract a1, a2, a8 constants. They finished with the finding that drilling expense can be minimized by about 10 percent using relatively simple equations for optimization. The following is a description of the equations(Bourgoyne A.T. Jr., Young F.S. 1974)
Rate of penetration is expressed as:

$ROP = Exp(a_1 + \sum_{j=2}^{8} a_j x_j)$

ROP=(f1)(f2)(f3)(f4)----(fn)

$f1 = e^{2.303a1}$

$f2 = e^{2.303a2(1000-D)}$

$f3 = e^{(2.303a3D^{(0.69(gp-9.0))})}$

$f4 = e^{(2.303a3D^{(0.69(gp-pc))})}$

$f5 = ((w/db)-(w/db)t)/(4-(w/db))^{a5}$

$f6 = (N/60)^{a6}$

$f7 = e^{(-a7h)}$

$f8 = (F_j/1000)^{a8}$

Where;

$ROP = Rate\ of\ penetration$

h = Depth, ft

t = Time, hrs

$aj = Constants$

$xj = Drilling\ parameters$

RESULTS AND DISCUSSION

The datasets consist of 3 wells:

1. Well A is located in the Amal field in southeastern Libya
2. Well B is located in Al-Sharara Field in southwest Libya
3. Well C is located in Al-Sarir field in the southeast of Libya.

The following **table**s show the statistical results of the experimental correlations of penetration rate, comparing them to the actual, and calculating the error rate in each equation. It was suggested to adopt the best equation for each field later.

Formation Characteristics, equations constants, Rock stresses and Bit specifications attached in each **table** separately

Case 1 : Amal field - Sirte Basin

Well – A

Formation Type: (ANHYDRITE - LIMESTONE - CLAYSTONE - SANDSTONE – SHALE)

Maurer (k = 0.25)-Bingham (α =1.7 and β =2.1)-Warren (a = 0.62/b = 0.87/c = 0.23). Rock strength in psi (Dolomite 415–Limestone 310–Sandstone 250)/Bit diameter 17.5 inch

Table 1: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	900	12.5	60	300	9.5	41.0
2	1000	12	65	302	9.6	42.0
3	1100	12.1	63	305	9.6	41.0
4	1200	11.6	66	301	9.7	41.0
5	1300	11.4	65	298	9.6	40.0
6	1400	11.2	63	297	9.8	39.0
7	1500	10.4	75	299	9.8	38.0
8	1600	10.2	72	301	9.9	37.0
9	1700	10	77	310	10.0	43.0
10	1800	9	95	305	10.0	43.0
11	1900	8.7	96	302	10.1	42.0
12	2000	8.4	102	301	10.7	42.0
13	2100	8.1	103	300	10.4	41.0
14	2200	7.7	95	295	10.3	40.0
15	2300	7.5	90	294	10.3	39.0

Table 2: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	81	90.11	53.48	124.19	104.94	72.09
2	77	88.78	53.17	118.69	99.70	68.53
3	76	85.77	52.44	116.04	100.57	67.64
4	72	84.79	50.28	112.71	94.97	64.08
5	67	82.29	47.74	110.01	92.37	59.63
6	66	77.50	44.59	104.86	89.63	58.74
7	63	78.49	45.43	99.38	81.95	56.07
8	62	71.52	41.87	91.98	79.23	55.18
9	63	69.31	42.95	86.89	77.55	56.07
10	61	71.56	42.48	82.82	67.97	54.29
11	58	68.92	39.97	79.45	64.71	51.62
12	59	68.72	39.45	77.41	61.86	52.51
13	56	64.95	36.91	72.90	58.66	49.84
14	51	55.99	30.61	64.81	53.87	45.39
15	47	50.67	27.44	59.87	51.47	41.83
	Error %	**7%**	**13%**	**15%**	**11%**	**5%**

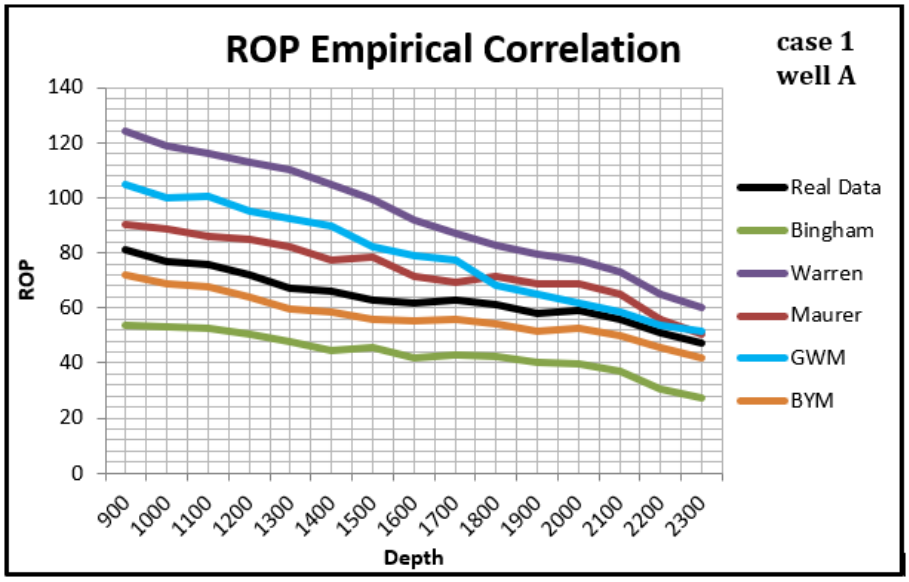

Figure 2: ROP Empirical Correlation (Case 1, well A)

Well – B

Formation Type: (ANHYDRITE - LIMESTONE - CLAYSTONE - SANDSTONE – SHALE)

Maurer (k = 0.27) - Bingham (α =1.56 and β = 1.78) - Warren (a = 0.51/b = 0.85/c = 0.27)

Rock strength in psi (Dolomite 450 – Limestone 310 – Sandstone 300)/Bit diameter 17.5 inch

Table 3: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	1200	9.3	71	247	10.5	47.0
2	1300	9.1	69	242	10.5	47.0
3	1400	8.8	76	244	10.3	46.0
4	1500	8.7	75	246	10.3	45.0
5	1600	8.8	72	248	10.2	44.0
6	1700	8.6	77	241	10.1	42.0
7	1800	8.9	73	247	10.0	42.0
8	1900	9.1	72	249	11.6	42.0
9	2000	9.4	74	253	11.5	39.0
10	2100	9.3	72	254	11.5	35.0
11	2200	9.1	70	247	11.2	46.0
12	2300	9.4	69	247	10.8	45.0
13	2400	9.1	66	247	10.6	45.0
14	2200	7.7	95	295	10.3	40.0
15	2300	7.5	90	294	10.3	39.0

Table 4: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	88	94.33	54.46	72.34	62.40	77.97
2	84	91.13	51.47	70.87	60.13	75.19
3	80	92.67	54.31	68.74	57.75	71.25
4	79	87.70	52.82	65.48	56.64	70.15
5	79	84.53	51.45	64.39	57.37	70.17
6	77	91.41	53.43	67.37	55.81	68.38
7	81	88.83	52.93	67.20	58.48	72.33
8	84	89.83	53.71	68.42	60.43	74.54
9	89	95.52	57.54	71.78	63.76	79.24
10	85	90.41	55.22	68.86	62.50	75.88
11	83	89.05	52.22	68.77	60.23	74.06
12	88	93.66	53.65	72.84	63.23	78.07
13	80	83.96	49.23	66.74	59.81	71.17
	Error %	**4%**	**17%**	**9%**	**14%**	**5%**

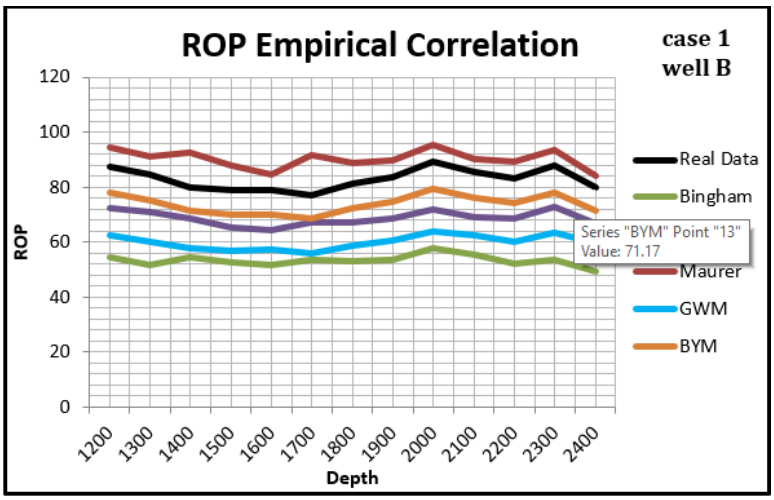

Figure 3: ROP Empirical Correlation (Case 1, well B)

Well – C

Formation Type: (ANHYDRITE - LIMESTONE - CLAYSTONE - SANDSTONE – SHALE)

Maurer (k = 0.23) - Bingham (α =1.6 and β = 2.4) - Warren (a = 0.54 / b = 0.84 / c = 0.26)

Rock strength in psi (Dolomite 430 – Limestone 300 – Sandstone 290) / Bit diameter 17.5 inch

Table 5: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	1800	16.3	61	304	10.7	44.0
2	1900	15.6	59	307	10.6	42.0
3	2000	15.7	62	309	10.2	42.0
4	2100	15.1	58	302	10.1	41.0
5	2200	14.8	66	300	10.8	41.0
6	2300	14.6	65	301	10.8	40.0
7	2400	14.5	64	298	10.7	38.0
8	2500	13.9	62	297	10.7	38.0
9	2600	14.2	60	291	10.5	45.0
10	2700	13.9	61	297	10.4	44.0
11	2800	13.9	58	304	10.0	42.0
12	2900	14.2	63	311	9.8	40.0
13	3000	14.3	61	322	9.5	40.0
14	3100	14.1	57	317	9.5	38.0
15	3200	14.5	55	312	11.5	36.0
16	3300	14.6	53	321	11.4	41.0

Table 6: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	121.74	138.71	87.58	153.93	134.88	105.91
2	106.76	121.24	76.81	136.63	118.28	92.88
3	114.45	127.87	82.33	140.84	126.80	99.57
4	96.75	115.09	69.60	130.73	107.19	84.17
5	105.59	128.18	75.97	137.18	116.99	91.87
6	99.67	121.04	71.70	130.45	110.42	86.71
7	97.33	120.76	70.02	131.08	107.83	84.68
8	85.20	108.23	61.29	119.22	94.39	74.12
9	86.78	113.86	62.43	127.33	96.15	75.50
10	83.82	106.49	60.31	118.18	92.87	72.93
11	79.43	96.36	57.14	109.47	88.00	69.10
12	90.97	104.53	65.44	114.30	100.78	79.14
13	88.83	95.08	63.90	105.53	98.41	77.28
14	80.92	89.75	58.22	102.77	89.65	70.40
15	82.81	93.89	59.58	109.30	91.75	72.05
16	81.40	86.90	58.56	102.91	90.19	70.82
	Error %	**7%**	**16%**	**12%**	**5%**	**5%**

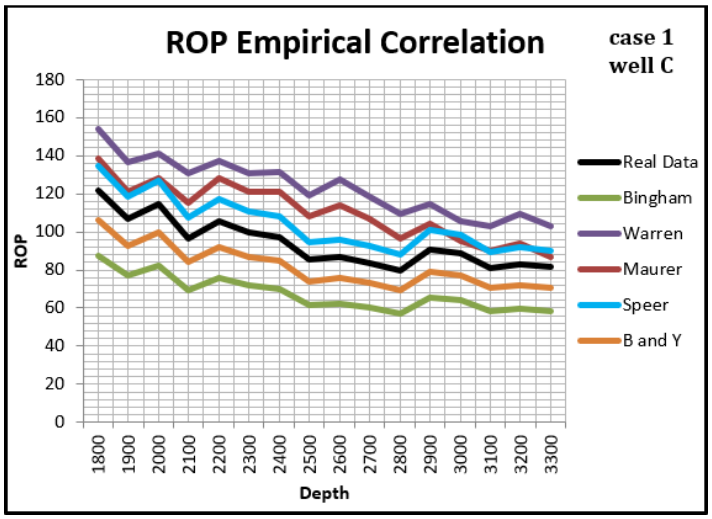

Figure 4: ROP Empirical Correlation (Case 1, well C)

Case 2 : Al-Sharara field - Mesozoic Basin
Well – A
Formation Type: (DOLOMITE - SHALE - LIMESTONE - SANDSTONE)
Maurer (k = 0.21) - Bingham (α =1.76 and β = 2.2) - Warren (a = 0.57 / b = 0.79 / c = 0.26)
Rock strength in psi (Dolomite 440 – Limestone 320 – Sandstone 270) / Bit diameter 17.5 inch

Table 7: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	600	10.0	77.0	306.0	10.0	47.0
2	700	9.7	78.3	308.0	10.0	46.0
3	800	9.7	74.7	311.1	9.8	46.0
4	900	9.8	77.0	307.0	9.8	45.0
5	1000	9.7	76.0	304.0	9.7	44.0
6	1100	9.9	66.0	302.9	9.6	43.0
7	1200	9.7	76.2	305.0	9.5	48.0
8	1300	9.6	77.1	307.0	9.2	48.0
9	1400	9.5	81.0	316.2	11.2	47.0
10	1500	9.4	82.0	311.1	11.0	46.0
11	1600	9.3	79.0	308.0	10.9	42.0
12	1700	9.4	76.3	307.0	10.8	40.0
13	1800	9.4	81.2	306.0	10.7	46.0
14	1900	9.0	83.2	300.9	10.4	44.0
15	2000	8.8	84.3	299.9	10.2	42.0
16	3300	14.6	53	321	11.4	41.0

Table 8: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	49.5	59.3	41.8	68.3	63.8	54.4
2	44.6	56.7	40.3	64.8	60.7	49.1
3	44.6	53.2	38.6	62.3	57.7	49.1
4	46.6	57.5	40.7	66.3	61.9	51.2
5	43.7	56.5	39.1	65.5	61.0	48.0
6	40.7	51.3	35.5	63.7	57.5	44.8
7	45.6	56.2	39.2	65.2	60.7	50.1
8	44.6	54.8	38.6	63.1	58.9	49.1
9	46.6	53.1	39.6	59.8	56.5	51.2
10	43.7	54.4	39.2	60.8	57.6	48.0
11	44.2	52.3	36.9	59.6	56.0	48.6
12	45.1	52.0	36.5	60.2	56.1	49.6
13	43.2	55.2	38.4	62.0	58.6	47.5
14	45.0	53.5	35.7	59.4	56.5	49.5
15	41.2	52.3	34.5	57.7	55.0	45.3
	Error %	**12%**	**6%**	**18%**	**15%**	**5%**

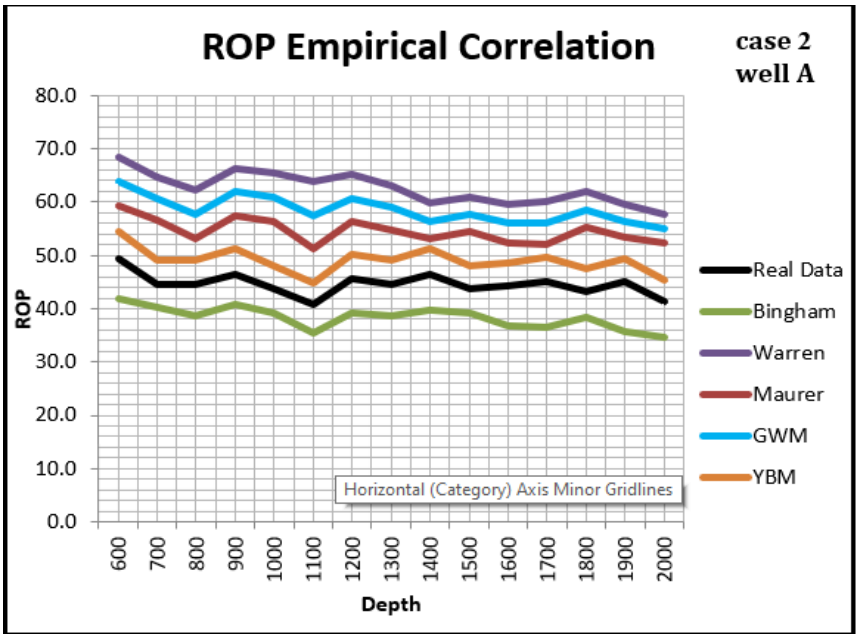

Figure 5: ROP Empirical Correlation (Case 2, well A)

Well – B

Formation Type: (DOLOMITE- SHALE - LIMESTONE - SANDSTONE)

Maurer (k = 0.21) - Bingham (α =1.92 and β = 2.1) - Warren (a = 0.57 / b = 0.79/c = 0.26)

Rock strength in psi (Dolomite 450 – Limestone 350 – Sandstone 290)/Bit diameter 17.5 inch

Table 9: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	2100	12.3	61	346.6	9.7	41.0
2	1900	12.1	59	350.0	9.6	41.0
3	2000	12.4	61	352.3	9.6	40.0
4	2100	12.7	58	344.3	9.5	40.0
5	2200	12.5	57	342.0	9.4	43.0
6	2300	12.7	60	343.1	9.8	42.0
7	2400	12.2	68	339.7	9.6	42.0
8	2500	12.1	63	338.6	9.6	41.0
9	2600	12.1	64	331.7	9.5	41.0
10	2700	11.9	71	338.6	9.4	40.0
11	2800	12.2	72	346.6	9.2	39.0

Table 10: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	65.70	55.83	61.10	81.66	76.97	72.27
2	62.20	51.25	57.84	76.04	72.23	68.42
3	64.65	54.92	60.12	80.33	75.72	71.11
4	69.54	57.35	64.68	85.71	81.10	76.50
5	67.58	55.33	62.85	83.32	78.83	74.34
6	72.48	59.72	67.41	87.96	83.85	79.73
7	74.44	63.72	69.23	88.93	85.41	81.88
8	67.61	58.47	62.88	84.32	79.35	74.37
9	69.54	61.87	64.68	88.62	82.56	76.50
10	72.48	63.73	67.41	87.30	83.52	79.73
11	76.40	64.84	71.05	88.28	86.16	84.04
	Error %	11%	4%	15%	13%	5%

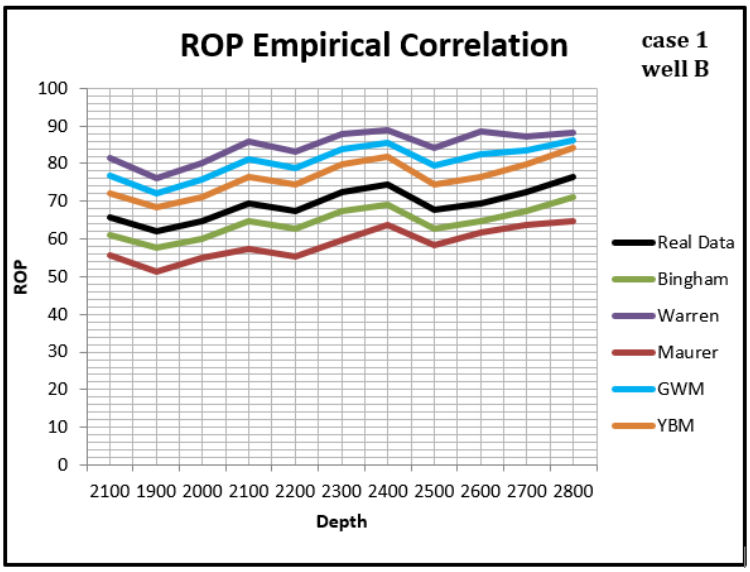

Figure 6: ROP Empirical Correlation (Case 1, well B)

Well C

Formation Type: (DOLOMIT - SHALE - LIMESTONE - SANDSTONE)

Maurer (k = 0.24) - Bingham (α =1.55 and β = 1.86) - Warren (a = 0.54/b = 0.63/c = 0.41)

Rock strength in psi (Dolomite 460 – Limestone 370 – Sandstone 300)/Bit diameter 17.5 inch

Table 11: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	2400	15.2	68.0	415.1	12.5	43.0
2	2500	14.9	69.0	410.4	12.1	44.0
3	2600	14.6	66.0	399.7	12.1	43.0
4	2700	14.9	64.0	398.1	11.9	43.0
5	2800	14.2	63.0	395.0	11.5	42.0
6	2900	15.1	62.0	418.1	11.4	41.0
7	3000	14.7	60.0	424.3	11.1	40.0
8	3100	15.0	58.0	425.8	10.8	39.0
9	3200	14.3	57.0	419.7	10.5	45.0
10	3300	14.7	55.0	412.0	10.4	45.0
11	3400	14.3	57.0	419.7	10.2	44.0
12	3500	14.2	52.0	422.8	9.9	44.0
13	3600	14.6	49.0	428.9	9.8	43.0

Table 12: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	88.0	75.7	93.2	102.2	81.87	92.40
2	87.0	75.5	92.5	101.2	81.26	91.35
3	87.0	73.1	86.5	100.1	80.07	91.35
4	90.1	74.4	85.8	103.3	82.27	94.61
5	81.1	67.6	80.1	94.5	74.33	85.11
6	80.9	67.1	84.4	94.6	74.00	84.90
7	72.7	59.8	79.3	85.5	66.24	76.30
8	73.3	59.8	78.3	86.8	66.52	76.95
9	67.7	55.0	73.0	80.5	61.34	71.10
10	72.4	58.2	72.7	86.6	65.25	75.97
11	67.7	55.0	73.0	80.5	61.34	71.10
12	61.6	48.7	66.1	74.4	55.15	64.66
13	59.0	47.1	64.2	74.0	53.07	61.95
	Error %	**11%**	**4%**	**15%**	**8%**	**4%**

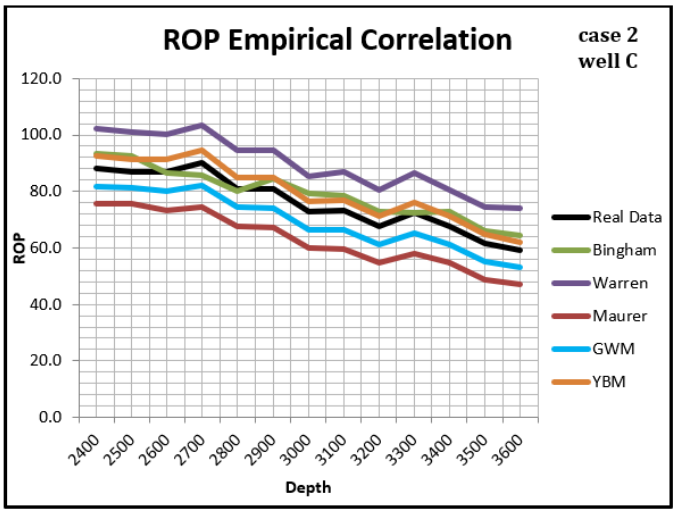

Figure 7: ROP Empirical Correlation (Case 2, well C)

Case 3 : Al-Sarir field - Sirte Basin
Well A
Formation Type: (SHALE-ANHYDRITE- LIMESTONE - CLAYSTONE - SANDSTONE)

Maurer (k = 0.26) - Bingham (α =1.57 and β = 2.5) - Warren (a = 0.57/b = 1.1/c = 0.77)
Rock strength in psi (Dolomite 520 – Limestone 370 – Sandstone 280)/Bit diameter 17.5 inch

Table 13: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	1200	13.8	71.8	470.0	13.4	45.0
2	1300	13.7	69.8	466.0	13.2	46.0
3	1400	13.4	71.8	467.6	13.1	45.0
4	1500	13.4	73.8	465.8	13.0	45.0
5	1600	13.2	72.8	462.2	13.0	44.0
6	1700	13.0	70.8	461.0	12.8	43.0
7	1800	12.7	72.8	468.0	12.7	42.0
8	1900	12.6	72.8	463.0	12.7	41.0
9	2000	12.8	74.9	465.0	12.6	47.0
10	2100	12.6	72.8	473.0	12.5	47.0
11	2200	12.5	70.8	481.0	12.5	46.0
12	2300	12.3	69.8	494.6	12.1	46.0
13	2400	12.6	66.8	501.8	11.9	45.0
14	2500	12.4	64.0	499.6	11.8	45.0
15	2600	12.2	60.0	501.7	11.8	45.0

Table 14: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	73.8	55.4	66.5	43.9	49.66	81.2
2	70.2	54.1	63.7	43.5	48.79	77.2
3	66.0	53.4	62.7	42.4	47.87	72.6
4	63.4	55.3	64.4	43.4	49.33	69.8
5	65.6	53.4	60.7	42.2	47.80	72.1
6	64.0	50.3	56.4	40.2	45.28	70.4
7	57.2	48.4	55.4	38.2	43.30	63.0
8	56.0	48.8	54.5	38.5	43.68	61.6
9	57.0	51.0	57.8	39.8	45.40	62.7
10	51.8	46.8	54.5	36.9	41.86	56.9
11	46.6	42.9	51.3	34.3	38.58	51.2
12	41.5	39.0	49.0	31.3	35.15	45.7
13	42.5	37.6	49.2	30.9	34.25	46.7
14	37.8	35.5	45.7	29.7	32.56	41.5
15	34.0	31.9	41.1	27.5	29.69	37.4
	Error %	**11%**	**8%**	**18%**	**14%**	**7%**

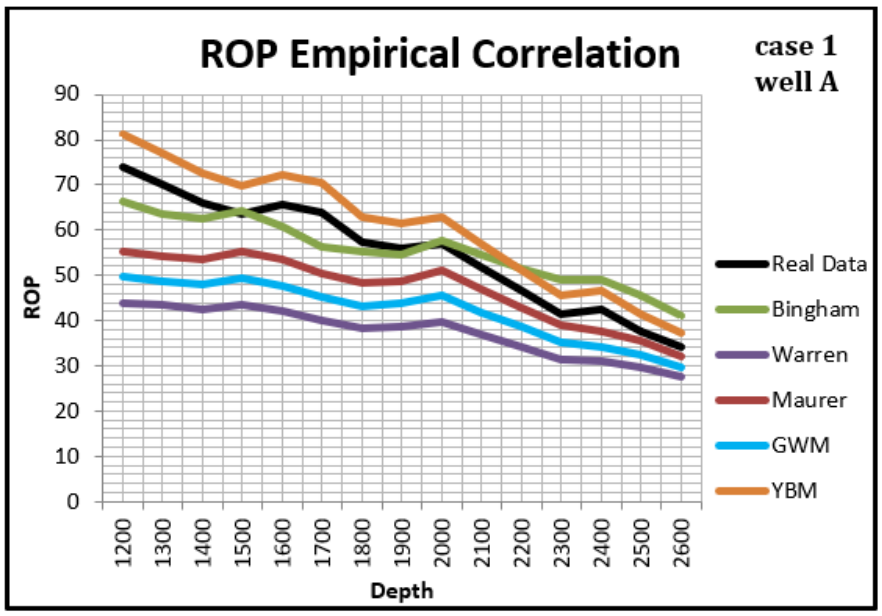

Figure 8: ROP Empirical Correlation (Case 1, well A)

Well B
Formation Type: (SHALE-ANHYDRITE - LIMESTONE - CLAYSTONE - SANDSTONE)
Maurer (k = 0.29) - Bingham (α =1. 7 and β = 2.6) - Warren (a = 0.54/b = 0.92 / c = 0.37)
Rock strength in psi (Dolomite 550 – Limestone 380 – Sandstone 270)/Bit diameter 17.5 inch

Table 15: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	plastic viscosity cp
1	2800	17.2	51.2975	522	11.5	51.0
2	2900	17.1	49.8525	517	11.4	48.0
3	3000	16.8	51.2975	519	11.4	47.0
4	3100	16.8	52.7425	512	11.2	46.0
5	3200	16.5	52.02	507	11.0	44.0
6	3300	16.2	50.575	505	10.8	41.0
7	3400	15.9	52.02	508	10.7	49.0
8	3500	15.8	52.02	512	10.6	48.0
9	3600	16	53.465	527	10.5	47.0
10	3700	15.8	52.02	519	11.8	44.0
11	3800	15.6	50.575	513	11.7	39.0
12	3900	15.4	49.8525	512	11.7	48.0
13	4000	15.7	47.685	510	11.6	46.0

Table 16: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	68	55.89	89.91	48.73	52.31	75.13
2	67	54.64	86.06	48.28	51.46	73.92
3	64	54.04	84.55	47.13	50.58	70.51
4	62	57.05	86.94	49.11	53.08	68.31
5	61	55.37	81.81	47.98	51.68	67.21
6	62	52.25	75.81	45.87	49.06	68.42
7	61	51.08	74.27	44.26	47.67	67.10
8	62	49.77	73.05	43.13	46.45	67.76
9	58	49.45	77.59	42.32	45.89	63.80
10	60	48.47	73.05	42.01	45.24	66.00
11	56	46.86	68.70	41.15	44.00	61.60
12	52	45.31	65.48	40.06	42.68	57.20
13	52	45.35	65.87	40.92	43.13	57.20
	Error %	**8%**	**19%**	**18%**	**16%**	**5%**

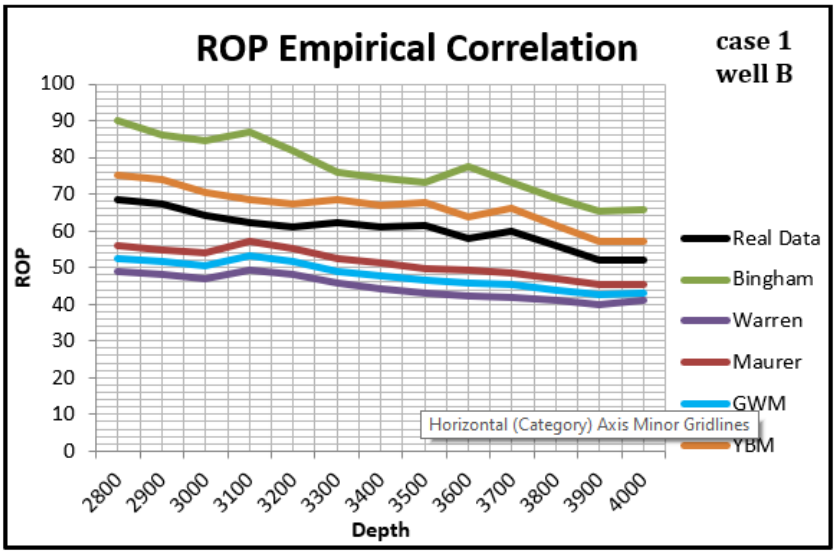

Figure 9: ROP Empirical Correlation (Case 1, well B)

Well C

Formation Type: (SHALE - ANHYDRITE - LIMESTONE - CLAYSTONE - SANDSTONE)

Maurer (k = 0.29) - Bingham (α =1. 7 and β = 2.6) - Warren (a = 0.54 / b = 0.92 / c = 0.37)

Rock strength in psi (Dolomite 550 – Limestone 380 – Sandstone 270) / Bit diameter 17.5 inch

Table 17: Experimental correlations of penetration rate

	Depth (ft)	WOB (kIb)	RPM(Rev/min)	Rock strength	MW ppg	Plastic viscosity cp
1	1800	17.2	51.2975	635.0	12.3	48.0
2	1900	17.1	49.8525	639.0	12.2	47.0
3	2000	16.8	51.2975	649.0	12.0	46.0
4	2100	16.8	52.7425	671.0	12.0	45.5
5	2200	16.5	52.02	701.0	11.9	44.0
6	2300	16.2	50.575	630.0	11.6	42.0
7	2400	15.9	52.02	655.0	11.4	40.0
8	2500	15.8	52.02	699.0	11.2	44.5
9	2600	16	53.465	723.0	13.2	43.0
10	2700	15.8	52.02	719.0	13.1	42.0
11	2800	15.6	50.575	645.0	12.8	40.0
12	2900	15.4	49.8525	698.0	12.7	47.0
13	3000	15.7	47.685	749.0	12.5	46.0
14	3100	16	45.5175	777.0	12.4	46.0
15	3200	16.3	43.35	810.0	12.2	45.0

Table 18: ROP (Real and empirical correlation)

	Real	Maurer	Bingham	Warren	GWM	YBM
1	66.87	61.21	77.51	48.02	54.62	73.55
2	65.79	58.06	74.30	46.13	52.09	72.37
3	62.75	55.90	73.34	43.87	49.89	69.03
4	60.80	53.77	75.40	41.70	47.73	66.88
5	56.00	46.87	71.29	36.58	41.73	61.60
6	60.89	54.39	66.38	42.95	48.67	66.98
7	58.00	49.85	65.35	38.90	44.38	63.80
8	52.00	43.22	64.38	33.75	38.49	57.20
9	47.00	42.58	68.16	32.86	37.72	51.70
10	51.00	40.85	64.38	31.90	36.38	56.10
11	46.28	48.11	60.75	38.01	43.06	50.91
12	48.06	39.47	58.09	31.39	35.43	52.87
13	43.00	34.07	58.14	27.65	30.86	47.30
14	39.00	31.39	58.03	26.00	28.69	42.90
15	35.00	28.55	57.73	24.17	26.36	38.50
	Error %	**8%**	**12%**	**17%**	**11%**	**5%**

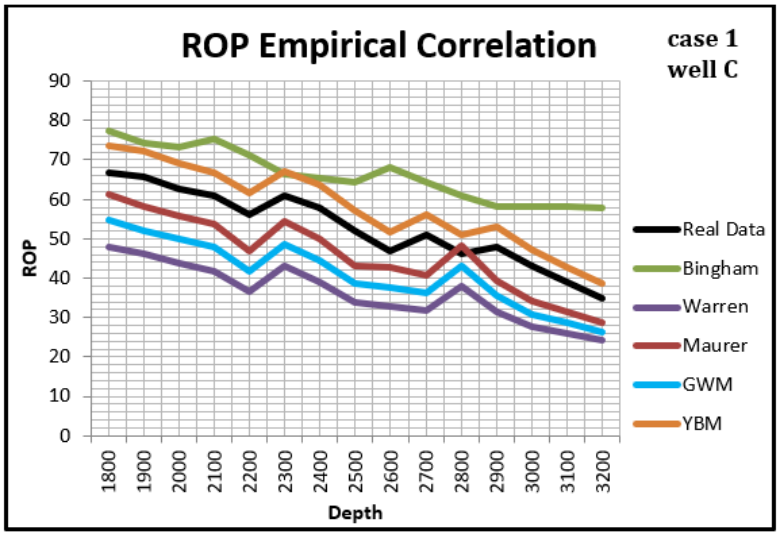

Figure 10: ROP Empirical Correlation (Case 1, well C)

CONCLUSION AND RECOMMENDATIONS

empirical correlations is used to predict Rate of Penetration (ROP) with taking into account the drilling parameters namely RPM, WOB, Torque and Rock strength

In case 1, the best and closest equation to real and the least error rate is (BYM) then (Maurer). Therefore, I recommend using it for an (ROP) account in the Amal field

In case 2, the closest equation to reality and the least error rate was (YBM) then (Bingham). Therefore, I recommend using it to calculate the (ROP) in the Al-Sharara field

In case 3, the closest equation to reality and the least error rate is (YBM) then (Maurer) . So I recommend to use it to calculate the (ROP) in the bed field

The worst equation was (Warren) and gave unsatisfactory results in the fields that i were studied, so I do not recommend it to calculate the penetration rate

In general, (YBM) is the best equation to predict the rate of penetration in Libyan fields because it uses the Mathematic style (power series) in analyzing the characteristics and this gives the closest results to reality

Nomenclature

ROP = Rate of Penetration (ft/h)
WOB = Wight on bit (klb)
RPM = Rotation per Minot (rpm)
Db = Bit diameter (inch)
UCS = Rock strength (psi)
TRQ = rotary torque
K = Drill ability constant
D = true vertical depth (ft)
γf = Drilling fluid density
μ = Drilling fluid plastic viscosity (cp)
Fjm = Modified jet impact force function (klbf)
Cfd is the formation drill ability parameter
Gp = Pore pressure gradient (lbm/ft)
Cϱ =equivalent circulating density
h = fractional tooth dullness
Fj = hydraulic impact force beneath the bit force lb/f
α and β = constants determined for a given rock formation.
a1 to a8 = constant that must be chosen based on local drilling conditions
f1 = function represent the effect of formation strength and bit type on penetration rate.
f2 = Function account for the rock strength increase due to normal compaction with depth.
f3 =function model effect of under compaction experienced in abnormal pressure formation.
f4 =function model the effect of bit weight and rotary speed on penetration rate.
f5 & f6 = function of rock strength increase due to normal compaction with depth.
f7 = Function models the effect of tooth wear.
f8 = function model the effect of bit hydraulic on rate of penetration.

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