OPTIMIZATION OF WEIGHT ON BIT DURING DRILLING OPERATION BASED ON RATE OF PENETRATION MODEL

Sonny Irawan[1], Irwan Anwar[2]

Abstak

Optimasi pengeboran sangat penting selama operasi pengeboran. Optimasi pengeboran dapat menghemat waktu dan biaya operasi dan meningkatkan keuntungan. Pengeboran optimasi bertujuan untuk mengoptimalkan variabel terkendali selama operasi pengeboran seperti Weight on bit (WOB) dan kecepatan rotasi untuk mendapatkan tingkat pengeboran maksimum (ROP). Dalam studi ini, Bourgoyne dan Young ROP model yang telah memilih untuk mengukur efek dari beberapa parameter selama operasi pengeboran. Parameter seperti kedalaman, tekanan pori, kerapatan beredar setara, berat badan sedikit, kecepatan putar, pakai gigi sedikit, dan memaksa jet dampak yang diekstraksi dari laporan pengeboran yang sebenarnya. Model penetrasi lapangan dibangun menggunakan hasil dari metode statistik. Hasil dari analisis ini digunakan untuk menentukan nilai optimal berat badan pada bit yang memberikan operasi pengeboran yang optimal. Secara keseluruhan, penelitian ini memberikan model matematika lengkap untuk tingkat penetrasi yang dibangun oleh Bourgoyne dan Young. Dari penelitian tersebut konstanta yang mewakili beberapa variabel pengeboran telah ditentukan. Tingkat penetrasi lapangan telah diprediksi berdasarkan konstanta untuk setiap kedalaman data. Akhirnya, berat dioptimalkan pada bit telah dihitung untuk beberapa titik data hasil simulasi dan telah terbukti menggunakan simulator pengeboran.

Kata Kunci: Optimasi Pengeboran, Weight on Bit, Tingkat Penetrasi, Model Bourgoyne dan Young, Simulasi Pengeboran.

Abstract

Drilling optimization is very important during drilling operation. Optimization of drilling could save time and cost of operation and increases the profit. Drilling optimization aims to optimize controllable variables during drilling operation such as weight on bit (WOB) and bit rotation speed for obtaining maximum drilling rate (ROP). In this study, Bourgoyne and Young ROP model had selected to measure the effects of several parameters during drilling operation. Parameters such as depth, pore pressure, equivalent circulating density, bit weight, rotary speed, bit tooth wear, and jet impact force were extracted from actual drilling report. The penetration model for the field is constructed using the results from statistical method. The result from analysis was used to determine optimum values of weight on bit that give optimum drilling operation. Overall, this study provides complete mathematical model for rate of penetration that was constructed by Bourgoyne and Young. From the study the constants that represented several drilling variables had been determined. The rate of penetration for the field had been predicted based on constants for every data depth. Finally, optimized weight on bit had been calculated for several data points and the results had been simulated and proved using drilling simulator.

***Keywords*:** Drilling optimization, Weight on Bit, Rate of Penetration, Bourgoyne and Young model, Drilling simulator.

1. Sonny Irawan, JurusanTeknik Perminyakan Universitas Islam Riau

2. Irwan Anwar, Jurusan Teknik Mesin Universitas Islam Riau

1. INTRODUCTION

Development of oilfield is subject to drill in cost efficient manners. For that reason oilfield drilling operations will face hurdles to reduce overall costs, increase performances and reduce the probability of encountering problems. The increase in complexity for drilling operation has increase many problems thus result in critical cost consideration. Different methods from different disciplines are being used nowadays in drilling activities in order to obtain a safe, environmental friendly and cost effective well construction.

Optimization of drilling operation can be obtained by increasing drilling speed. In the drilling industry, the first well drilled in a new field generally will have the highest cost. With increasing familiarity to the area, optimized drilling could be implemented those decreasing costs of each subsequent well to be drilled until a point is reached at which there is no significance improvement.

Major drilling variables considered to have an effect on drilling rate of penetration are not fully comprehend and complex to model. There are many proposed mathematical models which attempted to combine known relations of drilling parameters. The proposed models worked to optimize drilling operation by mean of selecting the best bit weight and rotary speed to achieve minimum cost. Considerable drilling cost reductions have been achieved by means of using the available mathematical models.

The aims of this study is to determine the drilling parameters constants (a_1 until a_8) that represent several drilling parameters for the field such as formation strength, normal compaction, pressure differential, weight on bit , rotary speed, bit tooth wear and hydraulic. Secondly, is to predict rate of penetration versus depth for the filed base on the constants that have been determine. Lastly, to determine optimize value of weight on bit specifically for certain depth in order to have optimum drilling operation.

2. BOURGOYNE AND YOUNGS' RATE OF PENETRATION MODEL

Bourgoyne and Youngs' method is the most important drilling optimization method since it is based on statistical synthesis of the past drilling parameters. A linear penetration model is being introduced and multiple regression analysis over rate of penetration equation is being conducted. For that reason this method is considered to be the most suitable method for drilling optimization.

The model proposed by Bourgoyne and Young has been adopted for this project in order to derive equations to perform the ROP estimation using the available input data. This model has been selected because it is considered as one of the complete mathematical drilling models in use of the industry for roller-cone type of bits. Equation 1 gives the linear rate of penetration equation which is a function of both controllable and uncontrollable drilling variables. When the multiple regression process is performed the model has been modified based on controllable parameters.

$$\frac{dF}{dt} = e^{\left(a_1 + \sum_{j=2}^{8} a_j x_j\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Formation Strength Function, f_1

The coefficient for the effect of formation strength is represented by a_1. It has been considered that the less the value for this constant, the less the penetration rate. The coefficient includes also the effects of parameters not mathematically modeled such as; the effect of drilled cuttings. Other factors which could be included for future consideration but known to be under this function could be drilling fluid details, solids content, efficiency of the rig equipment/material, crew experience, and service contractors' efficiency.

The equation for the formation strength related effects are defined as in equation 2. The f_1 term is defined in the same unit as rate of penetration, for that reason it is called drillability of the formation of interest.

$$f_1 = e^{a_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Formation Compaction Function, a_2

There are two function allocated for the consideration of the formation compaction over rate of penetration. The primary functions for the effect of normal compaction trend defined by a_2. The primary effect of formation compaction considers an exponential decrease in penetration rate with increasing depth, as given in equation 3.

This function assumes increasing rock strength with depth due normal compaction.

$$f_2 = e^{a_2 X_2} = e^{a_2}(10000 - D) \quad \ldots\ldots\ldots\ldots\ldots(3)$$

The additional function considered to have an effect over the penetration rate in regards of the formation compaction is defined by the coefficient a_3. This function considers the effect of under compaction in abnormally pressured formation. Within over-pressured, formations rate of penetration is an increased behavior. There is an exponential increase in penetration rate with increasing pore pressure gradient as shown in equation 4.

$$f_3 = e^{a_3 X_3} = e^{a_3} D^{0.69}(gp - 9.0) \ldots\ldots\ldots\ldots\ldots(4)$$

Differential Pressure in the Bottom hole Function, a_4

The function for the pressure differential is defined by coefficient a_4. Effect of differential pressure in the bottom hole is considered to reduce penetration rate with decreasing depth. Whenever the differential pressure between the bottom hole and formation is zero the effect of this function is going to be equal to 1 in the overall process as shown in equation 5.

$$f_4 = e^{a_4 X_4} = e^{2.303 a_4} D(gp - pc) \quad \ldots\ldots\ldots\ldots(5)$$

Bit Diameter and Weight Function, a_5

The function for the bit diameter and weight is defined by coefficient a_5. The bit weight and bit diameter are considered to have direct effect over penetration rate, equation 6. $\left(\frac{W}{d_b}\right)t$ is the threshold bit weight, which ranging from 0.6 to 2.0. The magnitude for these parameters has been determined specifically based on the characteristics of the formation. The force at which fracturing begins beneath the tooth is called the threshold force. The given function is normalized for 4000 lbf per bit diameter.

$$f_5 = e^{a_5 X_5} = \left(\frac{\frac{W}{d_b} - \left(\frac{W}{d_b}\right)t}{4 - \left(\frac{W}{d_b}\right)t}\right)^{a_5} \quad \ldots\ldots\ldots\ldots\ldots(6)$$

Rotary Speed Function, a_6

The function for the rotary speed is defined by coefficient a_6. Direct relation of bit weight on penetration rate the rotary speed is also set to have a similar relation as shown in equation 7. The normalizing value to equalize the rotary speed function to 1 is taken to be an appropriate magnitude based on the actual rotation of the bit.

$$f_6 = e^{a_6 X_6} = \left(\frac{N}{100}\right)^{a_6} \ldots\ldots\ldots\ldots\ldots(7)$$

Tooth Wear Function, a_7

The function for the tooth wear is defined by coefficient a_7. The tooth wear function is used to determine the fractional tooth height, the highest tooth wear the less the penetration rate as shown in equation 8. In order to calculate the respective tooth height, a bit record for similar bit type that has been used within the same formation.

$$f_7 = e^{a_7 X_7} = e^{a_7(-h)} \ldots\ldots\ldots\ldots\ldots(8)$$

Hydraulic Function, a_8

The function for the hydraulic effect is defined by coefficient a_8. The hydraulics function represents the effects of the bit hydraulics. Jet impact force was chosen as the hydraulic parameter of interest, with a normalized value of 1.0 for f_8 at 1,000 lbf, as given in equation 9.

$$f_8 = e^{a_8 X_8} = \left(\frac{F_j}{1000}\right)^{a_8} \ldots\ldots\ldots\ldots\ldots(9)$$

3. MULTIPLE REGRESSION TECHNIQUE

Equation 3 through 9 define the general functional relations between penetration rate and other drilling variables, but the constants a_1 through a_8 must be determined before the equations can be applied. The technique used to determine constants a_1 through a_8 are through multiple regression analysis of detailed drilling data taken over short depth intervals.

Theoretically, only eight data points are required to solve for eight unknowns a_1 through a_8. However, in the practice Equation 1 models can be applied if the rotary drilling process has 100-percent accuracy. A sensitivity study of the multiple regression-analysis procedure indicated that the number of data points required to give results depends not only on the accuracy of

1. Sonny Irawan, JurusanTeknik Perminyakan Universitas Islam Riau
2. Irwan Anwar, Jurusan Teknik Mesin Universitas Islam Riau

Equation.1, but also on the range of values of the drilling parameters x_2 through x_8. When any of the drilling parameters, x_j, have constant through the interval analyze, a value for the corresponding regression constant, a_j, should be estimated from past studies and the regression analysis should be carried out for the remaining regression constants. As the number of drilling parameters included in the analysis is decreased, the minimum number of data required to calculate the remaining regression also decreased. In many applications, data from more than one well had to be combined in order to calculate all eight regression constants.

4. CASE STUDY

Field data taken from Kinabalu East–1 well – Malaysia are shown in Table 1. The primary drilling variables required for the regression analysis are depth, penetration rate, bit weight per inch of bit diameter, rotary speed, fractional tooth wear, jet impact force, mud density, and pore pressure gradient. To calculate the best values of the regression constants a_1 through a_8 using the data shown in the Table 1. The parameters x_2 through x_8 must be calculated using Equation 3 through 9 for each data entry. Eight equations with the eight unknown *a1* through *a8* can be obtained from x_2 through x_8.

Using 25 data points in the Table 1 the equations yields will be:

$$26\,a_1 + 34041\,a_2 - 106\,a_3 - 240884\,a_4 - 22.24\,a_5 + 5.41\,a_6 - 6.125\,a_7 + 0.24\,a_8 = 84$$

The results of eight equations were solved for eight unknowns and the constants, a_1 through a_8, are obtained.

Table 1: Constant *a1* until *a8*

Variable	Constant	Value
Formation Strength	a_1	3.91
Normal Compaction	a_2	9.45E-05
Under Compaction	a_3	6.86E-05
Pressure Differential	a_4	8.64E-05
Weight On Bit	a_5	0.37
Rotary Speed	a_6	2.23
Tooth Wear	a_7	0.025
Jet Impact Force	a_8	0.67

Rate of Penetration

After obtained the constant of a_1 until a_8, the rate of penetration model was constructed for the field. The prediction of rate of penetration using the constructed model and the actual rate of penetration taken from the actual drilling report was shown in Figure 1 (Appendix-1). Data number 1 until 8 of the penetration rate shown in Figure-1 was not accurate, due to during the statistical analysis, the data was still not represent the exact condition of the field. However, as more data were obtained, the values of rate of penetration become more accurate. This is shown at data number 9, 10, 12, 15, 16, 20, 23 and 25 in Table-1.

Optimum Weight on Bit

Prediction result of the data number 9, 10 and 15 shown in Table-1can be optimize using equation 10 and the results were shown in the Table 2.

$$\left(\frac{W}{d_b}\right)Opt = \frac{a_5 H_1 \left(\frac{W}{d_b}\right)max + a_6 \left(\frac{W}{d_b}\right)t}{a_5 H_1 + a_6} \quad\text{.................(10)}$$

Table 2: Optimized Value of Weight On Bit

Data Number	Depth (ft)	Rotary Speed (rpm)	Actual WOB(lb)	Optimized WOB(lb)
9	6592-6679	120	30000	23888
10	6679-7341	120	5000	23888
15	9660-10662	65	30000	8575

Simulation with Drill Sim 500

To prove the optimization results from calculation was reliable and produced significant results, simulation using DrillSim 500 was performed.

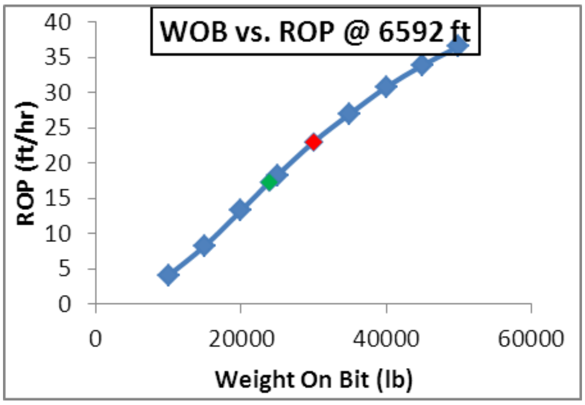

Figure 2: Simulation at 6592ft

Figure 2 illustrated the simulation of weight on bit versus rate of penetration for depth of 6592 ft. Rate of penetration increase at moderate values from 4.1ft/hr to 36.5ft/hr with increasing weight on bit. The optimum weight on bit is 23888lb while the actual weight on bit is 30000lb.

The optimum value of 23888 lb or 1950 lb/in of weight on bit can be use to have optimized drilling operation. This value valid as increasing weight on bit will increasing rate of penetration but only some of value subsequence increase in bit weight causes only slight improvements in penetration rate. This was can be happened when the slope had started declined and weight on bit was higher than 25000lb.

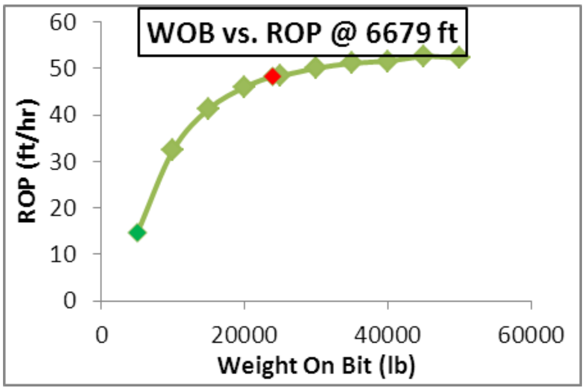

Figure 3: Simulation at 6679ft

Based on the graph obtain in Figure 3, rate of penetration increase from 14.7ft/hr to 52.3 ft/hr with increasing weight on bit. The slope increases rapidly form 5000lb until 25000lb. However, after 25000lb, rate of penetration increase slowly. Although the weight on bit has increase from 30000lb until 50000lb, rate of penetration still in the range of 50ft/hr.

For data number 10 with depth of 6679 feet, the optimum value of 23888 lb or 1950 lb/in of weight on bit can be use to have optimized drilling operation. This was very contrast with the value during actual drilling operation which is only 5000 lb or 408 lb/in of weight on bit. The value of 23888lb is accurate due to the rate of penetration was still at high value. However it could be seen that the rate of penetration slowly increased when higher weight on bit increased. This phenomenon occur due to reason that in soft type formations, excessive weight will only bury the teeth into the rock and cause increased torque, with no increase rate of penetration.

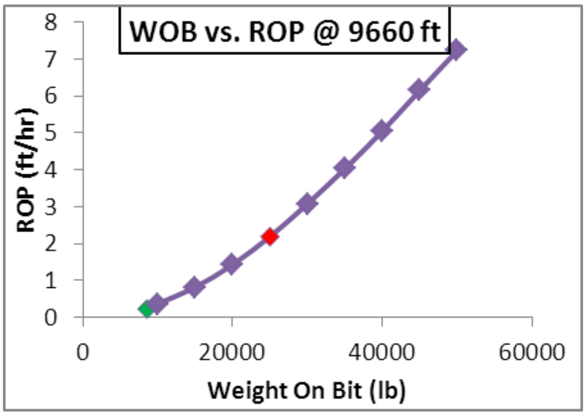

Figure 4: Simulation at 9660ft

In Figure 4 indicate the value of weight on bit versus rate of penetration for data at depth of 9660 ft. Rate of penetration increase at small ranges from 0.4ft/hr to 7.2ft/hr with increasing weight on bit from 8575lb to 50000lb.It shown that the optimize weight on bit is lower than the actual field value.

Data number 15 with depth of 9660 feet until 10662 feet the optimized bit weight was 8575 lb or 700lb/in in comparison to actual bit weight of 30000 lb during drilling operation. In 9660-10662 ft depth, the optimized bit weight was low due to formation high in strength. High value of bit weight in hard formation could reduce bit life which would reduce the optimization operation.

5. CONCLUSIONS

The results of optimization show the significance of this study. Determination of optimum weight on bit was very important in drilling operation as this parameter can be change during drilling operation. The optimization of weight on bit will optimize the whole drilling operation. Increasing rate of penetration will reduce the time need for drilling those reduces the cost for drilling operation.

1. The constants *a1* until *a8* which represent Formation Strength, Under Compaction, Normal Compaction, Pressure Differential, Weight On Bit, Rotary Speed, Bit Tooth Wear and Jet Impact Force had been achieved using Multiple Regression.
2. Bourgoyne and Young Model produce reliable Rate of Penetration model. Data number 9,10,12,15,16,20,23 and 25 predicted accurate Rate of Penetration compare with the actual Rate of Penetration obtained from the field.
3. Optimization for Weight on Bit found that for depth at 6592ft optimize Weight on Bit was 23888lb compare to 30000lb, at 6679 ft optimize value of Weight on Bit was 23888lb compare to 5000lb. For 9660ft optimize value was 8575lb compare to 30000lb.

The result of this study provides guidance for next drilling operation near the drilled well. The optimize values can be used as reference to obtain optimum drilling performance and reduces drilling cost.

Nomenclature

a_1 = formation strength constant
a_2 = normal compaction constant
a_3 = undercompaction constant
a_4 = pressure differential constant
a_5 = bit weight constant
a_6 = rotary speed constant
a_7 = tooth wear constant
a8 = hydraulic constant
d = bit diameter, in
d_n = bit nozzle diameter, in
D = well depth, ft
g_p = pore pressure gradient lb/gal
h = fractional tooth wear
H_1 = constants that depend on bit type
K = constant
N = rotary speed, rpm
q = flow rate, gal/min
W/d = weight on bit per inch of bit diameter, 1,000 lb/in.
$(W/d)_{opt}$ = optimum bit weight per inch
x_2 = normal compaction parameter
x_3 = undercompaction parameter
x_4 = pressure differential parameter
x_5 = bit weight parameter
x_6 = rotary speed parameter
x_7 = tooth wear parameter
x_8 = hydraulic parameter
ρ = mud density, lb/gal
ρ_c = equivalent circulating density, lb/gal

REFERENCES

Al- Betairi E.A., Moussa M., and Al-Otaibi S., "*Multiple Regression Approach to Optimize Drilling Operations in the Arabian Gulf Area*," SPE 13694, Middle East Oil Symposium, Bahrain, March 1985

Akgun F., *"How to Estimate Maximum Achievable Drilling Rate without Jeopardizing Safety*," SPE 78567, Abu Dhabi Inter. Pet. Exh. And Conf., October 2002

Bourgone A.T. Jr., Millheim K.K., Chenevert M.E., and Young F.S., "*Applied Drilling Engineering",* Society of Petroleum Engineers Text Book Series, Vol.1, Richardson, TX, 1986

Bourgoyne A.T. Jr., Young F.S., *"A Multiple Regression Approach to Optimal Drilling and Abnormal Pressure Detection"*, SPE 4238, August 1974.

Bingham M.G., *"A New Approach to Interpretting Rock Drillability*," re-printed from Oil and Gas Journal, April 1965

Cunningham, R.A. and Eenink. J.G., "*Laboratory Study of Effect of Overburden, Formation, and Mud Column Pressures on Drilling Rate of Permeable Formation*," Trans., AIME 1959.

Eckel, J.R., *"Microbit Studies of The Effect of Fluid Properties and Hydraulics on Drilling Rate*, II," SPE 2244, SPE, Dallas 1968

Estes, J.C., "*Guidelines for Selecting Rotary Insert Bits*," Pet. Eng, February 1974

Garnier A.J. and van Lingen N.H., "*Phenomena Affecting Drilling Rates at Depth,"* SPE 1097-G, Annual Fall Meeting of SPE, Houston, TX, May 1959

G Gabolde and J. P. Nguyen, *Drilling Data Handbook*, InstitutFrancais du Petrole

Publications Seventh Edition, Editions Technip, 1999 ISBN 2-7108-0756-4

Gelfgat Y.A., Gelfgat M. Y., and Lopatin Y.S., *"Advanced Drilling Solutions Lessons From the FSU"*, PennWell Corporation, Tulsa, OK, 2003, pp 199-290

Galle E.M and Woods A.B., *"Best Constant Weight and Rotary Speed for Rotary Rock Bits,"* Drill. And Prod. Prac., API 1963, pp 48-73

Kinabalu East-1, Final Drilling Report, Sabah Shell Petroleum Company Limited, 1990.

Maurer W.C., "*The 'Perfect-Cleaning' Theory of Rotary Drilling*," Journal of Pet. Tech, November 1962

Ozbayoglu M.E and Omurlu C., "*Minimization of Drilling Cost by Optimization of Drilling Parameters*,"15th International Petroleum and Natural Gas Congress and Exhibition of Turkey, 11-13 May 2005

Samuel G.R., and Miska S., *"Optimization of Drilling Parameters with the Performance of Multilobe Positive Displacement Motor (PDM),"* SPE 47791, IADC//SPE Asia Pacific Drilling Conference, Jakarta, Indonesia, September 1998

Stefan Miska., "*Developments in Petroleum Engineering",* Gulf Publishing Company, 1988, Vol-2, pp 265-275

Tibbits, G.A. et al., *"Effect OF Bit Hydraulics on Full Scale Laboratory Drilled Shale,"* J. Pet Tech 1180-88, July 1981

Vidrine. D.J.andBenit. E.J., *"Field Verification of Effect of Differential Pressure on Drilling Rate*," J. Pet Tech

Warren T.M., "*Penetration-rate Performance of Roller-Cone Bits,"* SPE 13259, SPE Annual Technical Conference, Houston, March 1986

Young F.S.Jr., "*Computerized Drilling Control,"* SPE 2241, SPE 43rd Annual Fall Meeting, Houston, October 1968

APPENDIX-1

Table 1: Field Data from Kinabalu East-1

Data Entry	*Depth (ft)*	*Bit Number*	*Drilling Rate (ft/hr)*	*Bit Weight (1,000 lb/in.)*	*Rotary Speed (rpm)*	*Tooth Wear*	*Jet Impact Force*	*ECD (lb/gal)*	*Pore Gradient (lb/gal)*
1	2150	2	171	0.82	120	-0.5	0.882	8.93	8.365
2	2155	7	20	0.57	110	-0.125	0.819	9.06	8.365
3	3591	8	160	0.82	120	-0.5	1.29	9.11	8.365
4	5190	10	82	1.63	120	-0.75	1.29	9.11	8.365
5	5872	11	49	2.45	120	-0.875	1.29	9.11	8.365
6	6000	12	43	2.45	120	-0.25	1.29	9.11	8.365
7	6080	16	64	1.63	120	-0.625	1.062	9.49	8.365
8	6322	17	36	2.45	120	-0.875	0.772	9.67	8.365
9	6592	18	27	2.85	120	-1	0.772	9.67	8.365
10	6679	19	14	0.41	120	-0.625	1.338	9.69	8.365
11	7341	20	83	1.63	180	-0.375	1.145	9.69	8.365
12	8921	21	46	1.63	180	0	1.216	9.68	8.365
13	9363	22	47	1.63	180	0	0.868	9.88	8.571
14	9652	23	19	2.85	100	-1	1.192	9.96	8.96
15	9660	24	3	2.45	65	-0.125	1.192	9.96	8.96
16	10662	25	34	1.22	180	0	1.097	9.96	8.91
17	10735	26	16	2.86	65	-0.125	1.192	9.96	8.9
18	10900	27	35	0.82	150	0	1.034	9.96	8.89
19	11214	28	12	3.27	70	-0.25	1.114	9.96	8.88
20	11224	31	5	2.94	100	-0.375	0.903	11.1	9.39
21	11481	32	26	1.76	170	0	0.975	11.02	9.37
22	12885	33	28	1.76	160	0	0.975	11.02	9.86
23	13180	34	11	1.76	130	0	0.825	10.96	10.12
24	13810	35	21	1.76	150	0	0.632	10.97	10.04
25	14300	37	15	1.76	160	0	0.632	10.95	9.98

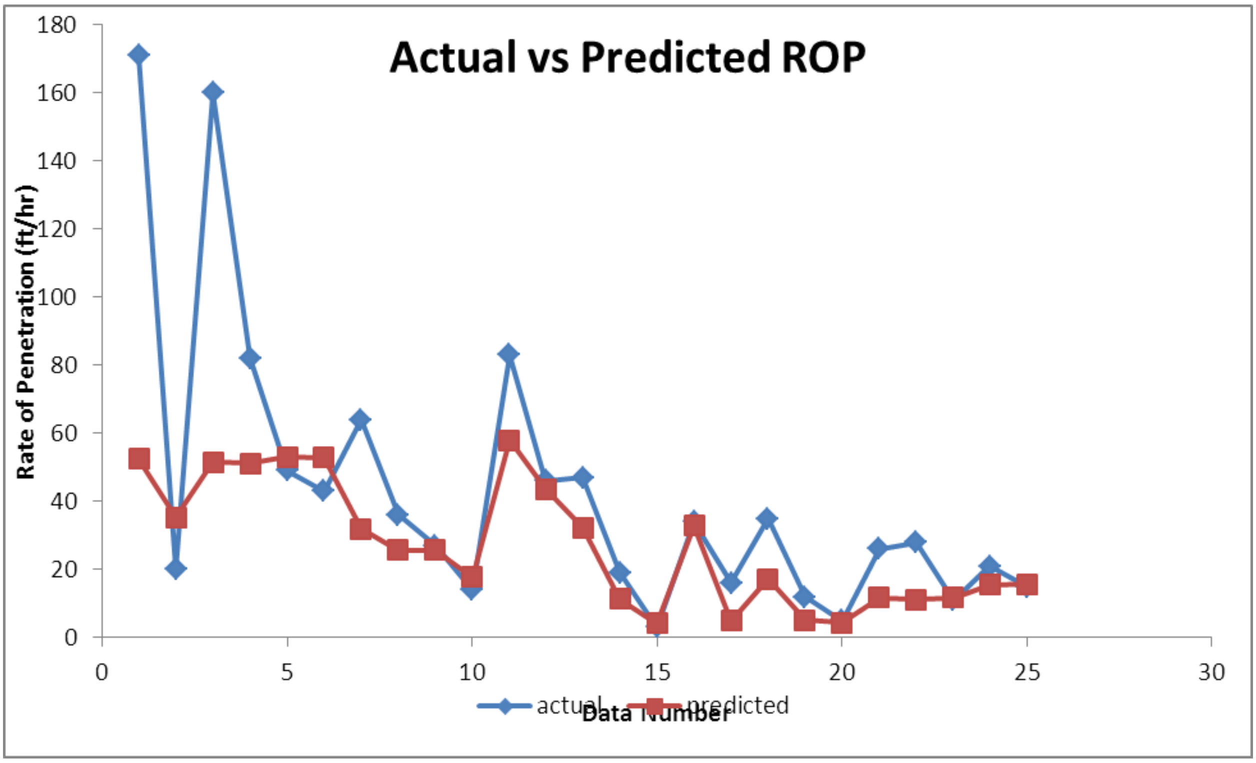

Figure 1: Actual vs. Predicted ROP for well Kinabalu East-1