ROP Modeling for Volcanic Geothermal Drilling Optimization

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ABSTRACT

Cost per Foot and Mechanical Specific Energy are two methods that are currently used in optimizing the actual rotary drilling process. Rate of penetration (ROP) is one of the most crucial factors to be analyzed in optimizing drilling operations. Rate of penetration is influenced by: 1) bit selection, 2) compressive strength and abrasiveness of formation, 3) drilling fluids properties, 4) weight on bit and rotational speed, 5) bit tooth wear, and 6) bit hydraulics. Given that most of the geothermal fields in Indonesia are located in areas with volcanic rock formations which characterized by high temperature, high compressive strength, and typically abrasive, the ROP equation that was formerly formulated by Bourgoyne and Young needs to be improved into justified ROP modeling for volcanic geothermal wells as a reference for well drilling optimization.

1. INTRODUCTION

Drilling optimization was first used in 1967 on drilling oil wells in order to reduce drilling costs. The principle of the optimization is to use the data of existed drilling wells in a field with similar geological structure characteristics for planning the drilling of wells at minimum cost.

Several theories and models of drilling optimization have been developed to optimize the selection of the drill bit type, weight on bit (WOB), rotary speed, and drilling fluid hydraulics. The most common method used to select the optimum drill bit is the cost per foot (Cf), meanwhile the drilling parameters optimization can be accomplished by modeling of the rate of penetration. The previous rate of penetration models which were developed by Bourgoyne and Young showed some simplified models including: 1) simplifying the rotary drilling process into one model, 2) developed equations to calculate the pore pressure, the optimum WOB, rotary speed, and hydraulics jet bits, and 3) provided a method to calibrate the model with field data. Bourgoyne and Young's rate of penetration model was developed based data from wells drilled previously combined with linear multiple regression methods.

The aims of this study are to optimize the selection of drilling bit by using specific energy and to optimize the drilling parameters with Bourgoyne and Young's rate of penetration models in the geothermal wells at field X in Indonesia.

2. BIT SELECTION

A common method to optimize the selection of drill bit is cost per foot. The drill bit which has the optimal value has the most inexpensive cost per foot.

$$C_f = \frac{C_b + C_r(t_t + t_c + t_b)}{\Delta D} \tag{1}$$

Equation (1) shows that the calculation of cost per foot (C_f) is influenced by five variables which are: the cost of drill bit (C_b), the cost of the rig (C_r), tripping time (t_t), depth intervals (ΔD), and drilling rotation time (t_b). In fact, it is not easy to obtain those variables data. The total trip time is the time of the trip for replacement drill bit. In practice, tripping is not only for the replacement of the drill bit, for example, but also for the time of casing installation. If those times included in the tripping time, then the calculation becomes invalid.

Bit performance that affect the intervals depth and bit lifetime (the frequency of the tripping) is influenced by several factors. It is not only influenced by the strength of the rock formations, but also influenced by the environment of geothermal wells, which have high pressure and high temperature. Rig price comparison studies may not be relevant if the different wells use a different rigs that have different prices. Because some of the costs per foot variables are difficult to determine, the other methods with not too many variables need to be used. One of them is mechanical specific energy (MSE) method.

Mechanical specific energy (MSE) is the energy required to lift each 1 cm^3 of rock from the borehole (Teale, 1965). Mechanical specific energy is influenced by the rate of penetration (ROP), weight on bit (WOB), and the rotary speed (Rotation per minute or RPM). Moore (1974) developed a simple equation of specific energy by considering the weight on bit, rotary speed, bit diameter, and the rate of penetration as shown in Equation 2.

$$E_s = \frac{2.35\, WOB\, RPM}{d\, ROP} \tag{2}$$

3. RATE OF PENETRATION MODEL

Several studies and experiments have been conducted in search of several factors in drilling operations that affect the rate of penetration. Several factors affect the rate of penetration: 1) bit types, 2) formation characteristics, 3) drilling fluid properties, 4) bit operating conditions (weight on bit and rotary speeds), 5) bit tooth wear, and 6) bit hydraulics (Bourgoyne, 1991). Bourgoyne and Young (1974) developed a rate of penetration formula in the following equations,

$$\frac{dD}{dt} = f_1 * f_2 * f_3 * f_4 * f_5 * f_6 * f_7 * f_8 \quad (3)$$

$$f_1 = e^{a_1}, f_2 = e^{a_2(10000-D)}, f_3 = e^{a_3 D^{0.69}(g_p-9)}, f_4 = e^{a_4 D(g_p-\rho)}, f_5 = \left[\frac{\frac{W}{d_b} - \left(\frac{W}{d_b}\right)_t}{4 - \left(\frac{W}{d_b}\right)_t}\right]^{a_5}, f_6 = \left(\frac{RPM}{100}\right)^{a_6}, f_7 = e^{-a_7 h}, f_8 = \left(\frac{F_j}{1000}\right)^{a_8} \quad (4)$$

To determine the value of the constants a_1 to a_8 those equations above are converted into the following equation,

$$\ln\frac{dD}{dt} = \ln f_1 + \ln f_2 + \ln f_3 + \ln f_4 + \ln f_5 + \ln f_6 + \ln f_7 + \ln f_8 \quad (5)$$

If all variables are expressed in x_1 to x_8, then the equation becomes

$$\ln\frac{dD}{dt} = x_1 a_1 + x_2 a_2 + x_3 a_3 + x_4 a_4 + x_5 a_5 + x_6 a_6 + x_7 a_7 + x_8 a_8 \quad (6)$$

3.1 Multiple Regression

The principle of multiple regression technique is a completed equation by using matrix multiplication operations. Using equation (6) above, each data can be obtained with the size of the data matrix as follows,

$$\begin{bmatrix} x1_1 & x2_1 & x3_1 & . & . & x8_1 \\ x1_2 & x2_2 & x3_2 & . & . & x8_2 \\ x1_3 & x2_3 & x3_3 & \vdots & \vdots & \vdots \\ . & . & . & . & . & . \\ x1_n & x2_n & x3_n & . & . & x8_n \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_k \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} \quad (7)$$

Constant values in the equation can be solved by matrix multiplication equation as shown below,

$$[Y] = [A^T A]^{-1} x\, [A^T b] \quad (8)$$

3.2 Weight on Bit and Rotary Speed Optimization

Weight on bit (WOB) and the rotary speed (RPM) optimum equations developed by Maratier are shown below,

$$\left(\frac{W}{d}\right)_{opt} = \frac{a_5 H_1 \left(\frac{W}{d}\right)_{max} + a_6 \left(\frac{W}{d}\right)_t}{a_5 H_1 + a_6} \quad (9)$$

$$N_{opt} = 100 \left[\frac{\tau_H}{t_b} \frac{\left(\frac{W}{d}\right)_{max} - \left(\frac{W}{d}\right)_{opt}}{H_3 \left[\left(\frac{W}{d}\right)_{max} - 4\right]}\right]^{\frac{1}{H_1}} \quad (10)$$

Value of H_1, H_2, and $(w/d)_{max}$ depend on the type of used bit, where rock's abrasivity constants are calculated from the classification of bits wear. The equations below are used to calculate the formation of abrasivity.

$$\tau_H = \frac{t_b}{J_2 \left(h_f + H_2 {h_f}^2/2\right)} \quad (11)$$

$$J_2 = \left[\frac{\left(\frac{W}{d_b}\right)_m - \left(\frac{W}{d_b}\right)}{\left(\frac{W}{d_b}\right)_m - 4}\right] \left(\frac{60}{N}\right)^{H_1} \left(\frac{1}{1 + H_2/2}\right) \quad (12)$$

Table 1: Value of H_1, H_2, and $(w/d)_{max}$, IADC classification.

Bit Class	H_1	H_2	H_3	$(W/d)_{max}$
1-1 to 1-2	1.9	7	1,0	7
1-3 to 1-4	1.84	6	0,8	8

2-1 to 2-2	1.8	5	0,6	8.5
2-3	1.76	4	0,48	9
3-1	1.7	3	0,36	10
3-2	1.65	2	0,26	10
3-3	1.6	2	0,20	10
4-1	1.5	2	0,18	10

Optimizing weight on bit and rotary speed may increase the rate of penetration, but the drilling process will not gain optimum when tooth wear condition can be increased. The level of bit wear can be represented from the depth interval which drilled by the bit (ΔD). Those depth intervals can be estimated by the following equations,

$$\Delta D = J_1 J_2 \tau_H \left[\frac{1 - e^{-a_7 h}}{a_7} + \frac{H_2\left(1 - e^{-a_7 h} - a_7 h_f e^{-a_7 h}\right)}{a_7^2} \right] \quad (13)$$

$$J_1 = f_1 * f_2 * f_3 * f_4 * f_5 * f_6 * f_8 \quad (14)$$

4. CASE STUDY

Drilling optimization method by using specific energy and Bourgoyne and Young's rate of penetration models are commonly used for oil and gas drilling. In this study, this method is used to optimize geothermal drilling. Six wells in Field X are used in this study, specifically at the altered andesite breccias lithology. Table 2 presents the well data.

Table 2: Well operations data at altered andesite breccias lithologies.

Well	Bit	Depth in (m)	Depth out (m)	Depth (ft)	Drilling Rate (ft/hr)	Bit Weight (1000 lb/in)	Rotary Speed (rpm)	Tooth Wear	Jet Impact Force (1000 lbf)	ECD (lb/gal)	Pore Grad. (lb/gal)	Hardness
DTM-26	NB #11	764	930	2778	49.1	1.06	135	-0.125	0.76	8.66	8.5	Soft
DTM-27	NB#3.3	790	938	2834	34.7	0.65	130	-0.125	1.001	8.33	8.5	Hard
DTM-27	NB#4.1	938	1277	3633	51.0	0.59	162.5	-0.25	1.001	8.66	8.5	Soft
DTM-31	NB #1	39	398	716	34.7	0.20	107.5	-0.125	0.668	8.58	8.5	Soft
DTM-31	NB #3	691	787	2424	13.9	1.03	105	-0.125	0.553	8.70	8.5	Hard
DTM-31	NB#4	833	843	2749	36.4	1.09	104	-0.125	0.553	8.66	8.5	Hard
DTM-31	NB#5	938	1326	3713	53.0	1.14	90	-0.25	0.833	8.75	8.5	Soft
DTM-32	NB #1	30	249	458	19.8	0.69	115	-0.125	0.727	8.58	8.5	Hard
DTM-32	NB #2	390	778	1916	28.0	0.91	96	-0.25	0.602	8.66	8.5	Soft
DTM-32	NB #3	778	1004	2922	34.3	1.03	100	-0.125	0.602	8.75	8.5	Hard
DTM-32	NB #5	1313	1700	4941	35.5	1.22	122.5	-0.25	0.526	8.75	8.5	Soft
DTM-34	NB #7	866	909	2911	23.7	1.43	90	0	0.902	8.58	8.5	Soft
DTM-35	NB #5	404	589	1629	24.1	0.74	96	-0.125	0.681	8.66	8.5	Soft
DTM-35	NB #7	754	982	2847	39.6	0.91	91.5	-0.25	0.646	8.75	8.5	Hard
DTM-35	NB #9	985	1323	3785	31.1	1.22	90	-0.125	0.721	8.66	8.5	Hard
DTM-35	NB #10	1323	1634	4849	27.6	1.55	110	-0.25	0.673	8.79	8.5	Hard

Generally, andesite breccias are soft because it is composed of fragments of rock that detach easily, but their hardness can be changed by alteration processes. There are two hardness criteria of andesite breccias in this study: soft and hard. Determination of the optimization bit selection in this study is by using the specific energy method. Comparison of specific energy value is performed on each hardness criterion. Figure 1 shows the specific energy values for each bit that is used in the altered andesite breccias lithology, soft and hard. In the soft formations, bit # 4.1 has a value of the lowest specific energy at depth intervals of around 750-1500 m. In the hard formation, bit NB # 7 has the lowest value of specific energy at around 500-1000 m depth of interval.

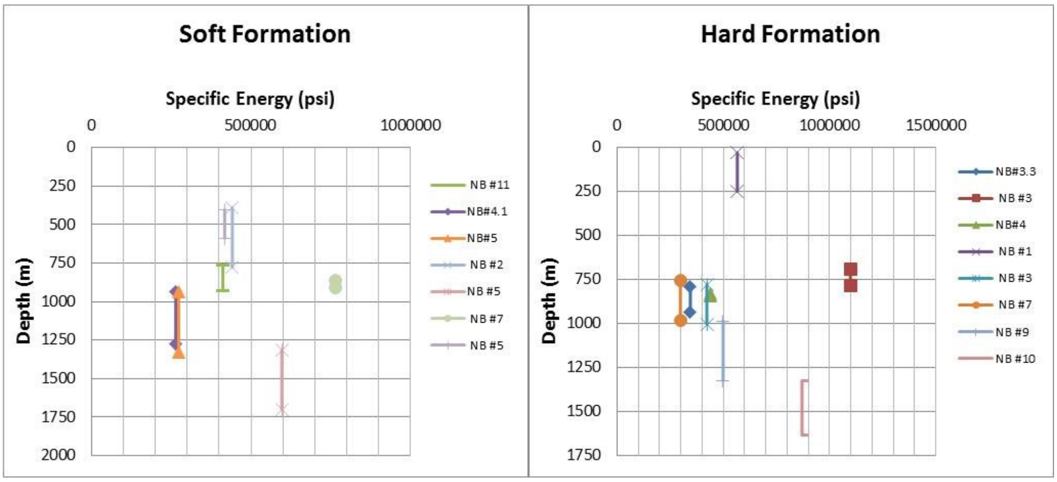

Figure 1: Specific energy of each bit at soft and hard formation.

The better data will generate positive values for the constants. The multiple regression results above show that the value of a_1, a_3, a_7, and a_8 are negative. This indicates that the data which used in this study is not that appropriate so it requires an additional amount of data. However, due to the limited number of wells that have been drilled, the amount of data required cannot be sufficient. Nevertheless, the two constants a_5 and a_6 parameters used to optimize the weight on bit and rotary speed are positive so that the results of the multiple regressions can still be used. Figure 2 shows the comparison of the rate of penetration of data and the simulation results with error about 6.7%.

Table 3: Results of drilling parameters calculation.

Well	Bit No.	x1	x2	x3	x4	x5	x6	x7	x8	ln (ROP)
Sumur 26	NB #11	1	7222	-118.89	-453.4	-1.327	0.300	-0.125	-0.274	3.893
Sumur 27	NB#3.3	1	7166	-120.54	481.8	-1.812	0.262	-0.125	0.001	3.546
Sumur 27	NB#4.1	1	6367	-143.06	-592.8	-1.917	0.486	-0.25	0.001	3.932
Sumur 31	NB#4	1	7251	-118.02	-448.6	-1.304	0.039	-0.125	-0.592	3.596
Sumur 31	NB#5	1	6287	-145.24	-915.2	-1.253	-0.105	-0.25	-0.183	3.971
Sumur 32	NB #3	1	7078	-123.12	-720.4	-1.358	0.000	-0.125	-0.507	3.536
Sumur 32	NB #5	1	5059	-176.90	-1218.0	-1.184	0.203	-0.25	-0.642	3.568
Sumur 34	NB #7	1	7089	-122.79	-232.6	-1.030	-0.105	0	-0.103	3.166
Sumur 35	NB #9	1	6215	-147.18	-617.7	-1.184	-0.105	-0.125	-0.327	3.439
Sumur 35	NB #10	1	5151	-174.62	-1397.4	-0.947	0.095	-0.25	-0.396	3.319

The table above shows the results of x_1 to x_8 calculation for each data. By using multiple regression technique the obtained value of the constants a_1 to a_8 are shown in Table 4.

Table 4: The value of constants a_1 to a_8.

a_1	-107.774
a_2	0.009772
a_3	-0.3486
a_4	0.000376
a_5	0.992084
a_6	1.144862
a_7	-4.86087
a_8	-0.45384

The next step in optimizing the penetration rate is determining the optimum weight on bit and rotary speed. The bit used in the optimization of weight on bit and rotary speed is bit with the number NB #4.1. From Table 1 it can be obtained bit NB # 4.1 specification for H_1, H_2, H_3, and $(w/db)_{max}$. By using Eqs. 11, 9, and 10, values of rock abrasivity are obtained up to 20.6 hrs. The optimum weight on bit is 6.1 (1000 lb/in) and the optimum rotary speed is 339 RPM. By using Eq. 13, the depth interval bit penetrated is 1350 ft, larger than the data 1112 ft. Thus, this condition is the optimum drilling conditions.

Figure 2: Rate of penetration between data and simulation.

Besides using the Maratier equation, optimum WOB and rotary speed can be determined by computational methods. The principles of the computational methods are finding the optimum value of ROP by calculating ROP values for some values of WOB and rotary speed. The computational methods are clarified with following stages:

1. Determine the values of weight on bit and rotary speed.
2. Calculate f_5 and f_6 by using Eq. 4, calculate J_1 by using Eq. 14.
3. Calculate J_2 by using Eq. 12 and ROP by using Eq. 3.
4. Calculate ΔD by using Eq. 13, and t_b can be calculate by dividing ΔD with ROP.
5. Assume the value of C_b, C_r, t_t, t_c, and total depth.
6. Calculate C_f by using Eq. 1, the number of bits that required is calculated by dividing total depth with ΔD
7. Back to Step (1) to calculate C_f for another value of WOB and rotary speed.
8. Determine WOB and rotary speed optimum by minimum cost per foot.

Figure 3 shows the correlation between cost per foot and rotary speed for each weight on bit at 0.5, 0.6, 0.7, 0.8, 0.9, and 1 (1000 lb/in). From the figure, it can be observed that for the rotational speed of 200 RPM the C_f gains the lowest value, so it can be concluded that the rotational speed of 200 RPM is the optimum amount. Figure 4 shows the relationship of cost per foot with weight on bit for several rotary speed values. The graph in Figure 4 shows that the increment in weight on bit will cause a decrease in the value of cost per foot. It is significantly up on the weight-on-bit 1000 lb/in. Increment on WOB after 1000 lb/in will be lowering the value of the CPF so the effect will not be significant. Furthermore, increasing the value of WOB can cause increment of bit wear rate. Thus increasing the WOB will not cause a decrease in CPF that will significantly more affect the process. Therefore, the optimum WOB to be used in this case is about 1000 lb/in.

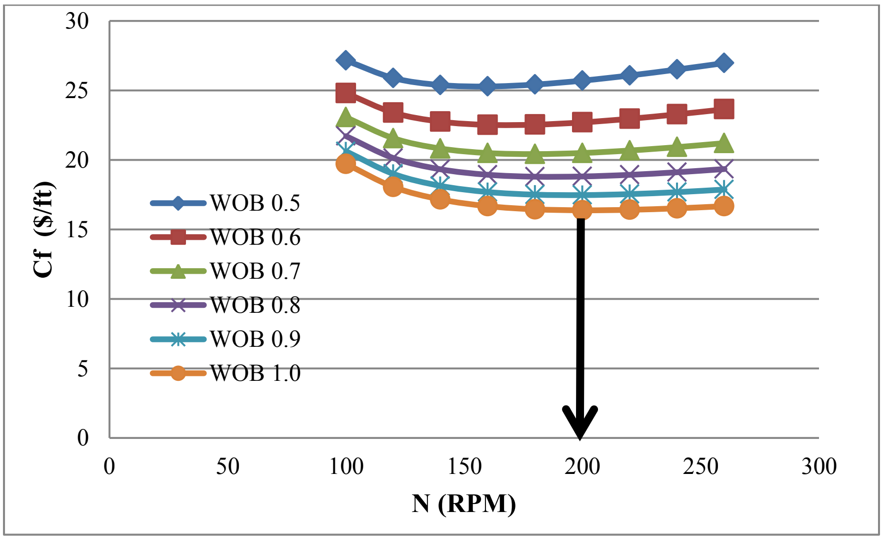

Figure 3: Cost per foot (C_f) vs rotary speed (N) for some value of weight on bit (WOB).

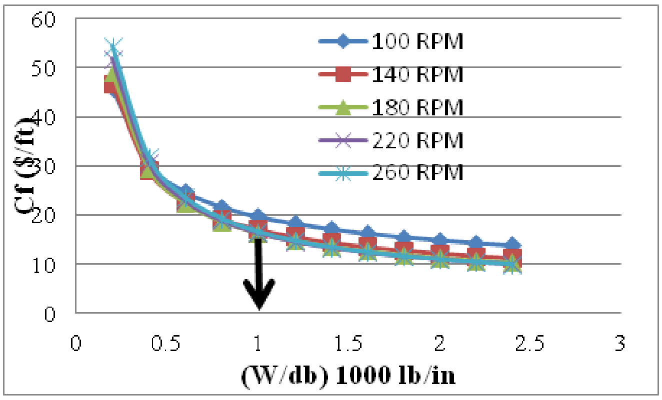

Figure 4: Cost per Foot (C_f) vs weight on bit (W/db) for some value of rotary speed.

5. CONCLUSION

- Bourgoyne and Young's rate of penetration models that were developed to optimize drilling in oil and gas wells can be used to optimize the parameters of geothermal drilling. This is because the parameters in the drilling of oil and gas wells is relatively the same as in geothermal wells, such as the type of bits, formation characteristics, drilling fluid properties, weight on bits, rotary speeds, bit tooth wear rates, and fluid hydraulics. Increasing the value of the parameter WOB and rotary speed generally will increase the rate of penetration of drilling up to the optimum point.
- The specific energy method can be used in optimizing the big selection on geothermal drilling as an alternative method of cost per foot. Bit of NB # 4.1 is the optimal use for soft altered andesite breccia lithology, whereas NB # 7 bit optimally can be used on hard lithology because it has the lowest SE values. Abrasivity in the soft formation like altered andesite breccias lithology in the field X is 20.6 hrs.
- The optimum weight on bit and rotary speed for bit NB # 4.1 by using Maratier is 6.1 (1000 lb/in) and 339 RPM, meanwhile by using the computational method the value will be 1000 lb/in and 200 RPM. Computational method is considered the most appropriate scheme to be used because it is based on the real data.

NOMENCLATURE

C_f = Drilling cost per foot, $/ft.
C_b = Cost of bit, $.
C_r = Rig operating cost, $/hr.
D = Depth, ft.
Es = Specific nergy, Kpsi
d_b = Bit diameter, in.
F_j = Jet impact force, lbf.
g_p = Pore pressure gradient, lbm/gal.
H_1, H_2, H_3 = Bit constants.
h = Fractional bit tooth wear, 1/8.
J_1, J_2 = Rate of penetration constants.
N_{opt}= Optimum rotary speed, rpm.
ROP= Rate of penetration, ft/hr.
t_b = Bit rotating time, hr.
t_c = Non-rotating time during the bit run, hr
t_t = Trip time, hr.
(W/db)= Bit weight per inch of bit diameter, 1000 lbf/in.
$(W/db)_{max}$= Maximum bit weight per inch of bit diameter, 1000 lbf/in.
$(W/db)_t$ = Threshold bit weight per inch of bit diameter at which the bit begins to drill, 1000 lbf/in.
x, a, y = Matrix values
τ_H = Formation abrasiveness constant
ΔD = Bit Footage, ft.
ρ= Equivalent mud density, lbm/gal.

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