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Determining Bourgoyne and Young Model Coefficients Using Genetic Algorithm to Predict Drilling Rate

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Abstract: In this research, GA is employed to determine constant coefficients of Bourgoyne and Young model and consequently predict drilling rate with high accuracy. Bourgoyne and Young model represents a general mapping between drilling rate and some drilling variables. There are eight unknown parameters in this model, which are dependent to the ground formation types. These eight parameters can be determined using previous drilling experiences. Previous drilling experiences include date sets of eight different drilling parameters such as depth, bit weight, rotary speed and pore pressure. In this research, sensory data of drilling nine different wells of Khangiran Iranian gas field has been collected to obtain needed sets. Bourgoyne and Young recommended multiple regression method to determine unknown coefficients. However, applying multiple regression method leads to physically meaningless values in some situations. Although, some new mathematical methods have recently been issued to reach meaningful results, applying them diminishes drilling rate prediction accuracy in practice. In order to reach more accurate prediction and physically meaningful coefficients, we applied Genetic Algorithm (GA) to determine unknown parameters of Bourgoyne and Young model. Afore-mentioned wells were considered for applying the new approach and testing it. Simulation results prove the proficiency of the new methodology to determine constant coefficients of Bourgoyne and Young model.

Key words: Drilling rate prediction, Bourgoyne and Young model, genetic algorithm

INTRODUCTION

Optimization drilling techniques succeed to reduce drilling costs noticeably. An essential part of these techniques is drilling rate prediction (Kaiser, 2007). Therefore, drilling engineers have been concerned about this issue considerably during last decades because it results in optimum drilling parameters selection, which leads to minimize drilling cost per foot (Bourgoyne *et al*., 2003).

Rate of penetration is affected by many parameters such as hydraulics, weight on bit, rotary speed, bit type, mud properties, formation characteristics, etc. (Akgun, 2007). There exists no exact mathematical relationship between drilling rate and different drilling variables because not only a large number of uncertain drilling variables influence drilling rate, but also their relationship is nonlinear and complex (Ricardo *et al*., 2007). However, scientists have tried to suggest some simplified models to create a mapping between drilling rate and its major variables. One of the most successful one is Bourgoyne and Young model (Bourgoyne and Young, 1999). In this model, there are some unknown parameters or coefficients, which must be determined based on previous drilling experience in the field. Therefore, the method of determining these coefficients has a significant impact on model accuracy.

In order to determine unknown coefficients, Bourgoyne and Young suggested multiple regression technique (Bourgoyne and Young, 1999). Nevertheless, applying multiple regression method does not guarantee reaching physically meaningful result. Furthermore, this method is limited to the number of data points.

To reach meaningful result, some new mathematical methods have recently been applied to find out these unknown parameters. For instance, Non-linear least square data fitting with trust-region method is a mathematical technique, which is applied to this problem recently (Bahari and Baradaran Seyed, 2007). This method is one of the optimization algorithms, which minimizes the sum of square errors function. The method is based on the interior-reflective Newton method. In each of iterations, the approximate solution of a large linear system is estimated using the method of Preconditioned Conjugate Gradients (PCG) (Coleman and Li, 1994, 1996). This technique makes it possible to determine lower

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and upper bounds for results and limit them to be in the reasonable ranges (Coleman and Li, 1996). However, computed coefficients using this scheme do not result in sufficiently accurate models in practice.

During the last two decades, evolutionary Algorithms such as GA have been applied to many optimization problems. For example, Justus Rabi (2006) applied GA to minimize harmonics in PWM inverters or Ikramullah But and Hou-Fang (2006) used it in scheduling flexible job shops. In this research, we applied GA to determine the optimal values of Bourgoyne and Young model unknown parameters. Since GA is able to handle linear constraints and bounds, it guarantees to reach physically meaningful result. Furthermore, using GA leads to a more accurate model in comparison with trust-region method.

KHANGIRAN GAS FIELD

As mentioned, 9 wells of Khangiran gas field were considered to apply and test the new scheme. Khangiran gas field is located in the northeast of Iran. This field was surveyed in 1937. In 1956, the stratigraphy plan was prepared and it was named in 1962. Figure 1 shows the stratigraphy column and geological description of each formation for a typical well in this field. Khangiran field includes three gas reservoirs:

- **Mozdouran:** The existence of sour gas in this reservoir was proved in 1968 and the production was started in 1983. It consists of thick layer limestone. Up to now, 37 wells have been drilled.
- **Shourijeh B:** This reservoir was explored in 1968 and production was started in 1974. Shourigeh formation is mainly formed from sandstone layers. So far, seven wells have been drilled and completed in the reservoir. The gas from this reservoir is sweet and H_2S free.
- **Shourijeh D:** This reservoir was explored in 1987 and after drilling the well, production was started in the same year. Seven wells have been drilled up to now. The gas from this reservoir is sweet, too.

Formations	Description
Khangiran	Silty shale and stily claystone
Chehelkaman	Dolomite and anhy drite to sandy limestone
Pestehligh	Silty shale and sandstone
Kalat	Micritic to cry staline limestone and dolomite
Neyzar	Calcareous sandstone, siltstone and shale
Abtalkh	Silty shale and mari
Abderaz	Micritic limestone, silty calcareous shale
Aytamir	Glaconitic sandstone
Sanganeh	Calcareous shale, clay stone and silty shale
Sarcheshmeh	Argilaceous micritic limestone, some shale
Tirgan	Oolitic argilaceous micritic limestone, mari, shale
Shourijeh	Oolitic sandstone and Calcareous silty shale
Mozdouran	Argilaceous limestone and oolitic dolomite limestone

Fig. 1: Stratigraphy column of a typical well in Khangiran field and formations description

BOURGOYNE AND YOUNG DRILLING RATE MODEL

Bourgoyne and Young have proposed the following equation to model the drilling process when using roller cone bits (1):

$$Rop = f_1 \times f_2 \times f_3 \times f_4 \times f_5 \times f_6 \times f_7 \times f_8 \quad (1)$$

where, Rop is rate of penetration (ft/hr). The function f_1 represents the effect of formation strength, bit type, mud type and solid content, which are not included in the drilling model. This term is expressed in the same unit as penetration rate and is often called the formation drillability. The functions f_2 and f_3 symbolize the effect of compaction on penetration rate. The function f_4 signifies the effect of overbalance on penetration rate. The functions f_5 and f_6 respectively, model the effect of bit weight and rotary speed on penetration rate. The function f_7 represents the effects of tooth wear and the function f_8 characterizes the effect of bit hydraulics on penetration rate (Bourgoyne *et al*., 2003). The functional relations in Eq. 1 are as follows:

$$f_1 = e^{2.303 a_1} = K \quad (2)$$

$$f_2 = e^{2.303 a_2 (10000 - D)} \quad (3)$$

$$f_3 = e^{2.303 a_3 D^{0.69} (g_p - 9)} \quad (4)$$

$$f_4 = e^{2.303 a_4 D(g_p - \rho_c)} \quad (5)$$

$$f_5 = \left[\frac{\frac{W}{d_b} - \left(\frac{W}{d_b}\right)_t}{4 - \left(\frac{W}{d_b}\right)_t}\right]^{a_5} \quad (6)$$

$$f_6 = \left(\frac{N}{60}\right)^{a_6} \quad (7)$$

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

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

Where:

a_1 to a_8	= Bourgoyne and Young model constant coefficients
D	= True vertical depth (ft)
d_b	= Bit diameter (in)
F_j	= Jet impact force (lbf)
g_p	= Pore pressure gradient (lbm gal^{-1})
h	= Fractional bit tooth wear
ñ$_c$	= Equivalent mud density (lbm gal^{-1})
N	= Rotary speed (rpm)
W	= Weight on bit (1000 lbf)
$(W/d_b)_t$	= Threshold bit weight per inch of bit diameter at which the bit begins to drill

As mentioned a_1 to a_8 are dependent to local drilling conditions and must be determined for each formation using prior drilling data sets obtained from the drilling area (Bourgoyne *et al*., 2003). Bourgoyne and Young recommended specific bounds for each of eight coefficient based on reported ranges for the coefficients from various formations in different areas (Bourgoyne *et al*., 2003; Bourgoyne and Young, 1999) and average values of them. Lower and upper bounds to achieve meaningful results have been suggested as shown in the Table 1. Using these bounds increases the reliability of the achieved predictor system.

Table 1: Bourgoyne and Young recommended bounds for each coefficient

Coefficients	Lower bound	Upper bound
a_1	0.5	1.9
a_2	0.000001	0.0005
a_3	0.000001	0.0009
a_4	0.000001	0.0001
a_5	0.5	0.2
a_6	0.4	0.1
a_7	0.3	1.5
a_8	0.3	0.6

Bourgoyne and Young employ multiple regression method to determine unknown coefficients. But, this scheme provides results out of recommended bounds in some situations. To be more precise, multiple regression method may result in negative or zero values. It is taken for granted that negative or zero values for coefficients are physically meaningless. For instance, if the weight on bit constant (a_5) is a negative value, it illustrates that increasing the weight on bit leads to reduce the penetration rate or a zero value implies that increasing the weight on bit has no effect on the drilling rate. Therefore, it is needed to apply new methods to gain an applicable predictor system.

DETERMINING BOURGOYNE AND YOUNG CONSTANT COEFFICIENTS USING GA

As mentioned, here employed GA to determine optimal value for constant parameters of Bourgoyne and Young model. Since, GA handles bound constraints, using it guarantees to find optimum values of coefficients in recommended bounds (not out of bounds). Therefore, GA not only provides meaningful result but also is not limited to the number of data points. Figure 2 shows architecture of the predictor system.

To find constant parameters of the aforementioned model for each formation, the following procedure was performed.

For each formation in Khangiran field, the daily drilling progress reports of 10 drilled wells (from the surface to the final reservoir depth) in this field were gathered initially. After the data quality control, nine wells having more accurate data were opted.

We constructed a database from available data of nine wells. The database includes quantities of D, W, N, g_p, ρ_c, h, F_j, d_b and achieved Rop in each formation. It must be noted that the fractional tooth wear (h) is expressed just at the end of bit running. Therefore, only drilling data

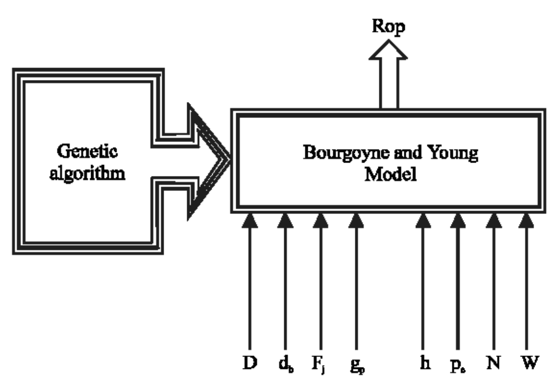

Fig. 2: Architecture of predictor system

at ending the bit run can be used. Table 2 provides a sample of the required data which is included in our database.

In each formation, by applying inputs (D, W, N, g_p, ρ_c, h and F_j) and output (Rop) to the above-mentioned model, we use GA to find out optimum values of eight unknown coefficients. GA was run in the following steps.

Step 1: Set the initial parameters for GA: population size, crossover type and probability and mutation probability.
Step 2: Set all bounds recommended by Bourgoyne and Young for each of eight parameters, particularly.
Step 3: Generate the initial population randomly.
Step 4: Reckoning of a fitness value for each subject. The considered fitness function is Standard Deviation of distances between real Rop and estimated Rop by predictor system.
Step 5: Selection of the subjects that will mate according to their share in the population global fitness.
Step 6: Apply the genetic operators (crossover, mutation...).
Step 7: Repeat Steps 3 to 6 until the generation number is reached.

RESULTS AND DISCUSSION

As mentioned, constants a_1 to a_8 were computed for each of Khangiran field formations utilizing GA. Table 3 shows the results obtained, using multiple regression method, trust-region method and proposed scheme for five formations of Khangiran field. As is rendered from the table, when the multiple regression method is applied, the resulting coefficients may be negative or zero (which is physically meaningless). While, computed coefficients gained by employing trust-region method and GA are all physically meaningful and in recommended bounds.

In Table 4 Standard Deviation (STD) error of drilling rate estimation by these two methods is illustrated. It can be interpreted that the proposed scheme is

Table 2: A sample of required data, obtained from wells daily drilling progress reports

Well No.	Rop ($ft\,h^{-1}$)	D (ft)	W (1000 lbf)	d_b (in.)	N (Rpm)	ρ_c ($lbm\,gal^{-1}$)	h (%)	g_p ($lbm\,gal^{-1}$)	F_j (lbf)
Well 50	50.6	354	17.5	26.0	130	08.82	0.25	7.48	960
Well 50	41.5	1411	15.0	17.5	130	09.96	0.25	8.62	1776
Well 47	24.3	359	15.0	26.0	130	08.95	0.25	7.62	1611
Well 47	14.9	1519	10.0	17.5	110	10.20	0.38	8.82	2123
Well 46	07.3	1772	07.5	17.5	110	10.30	0.25	8.95	1185
Well 42	09.5	1969	10.0	17.5	110	10.80	0.50	9.49	1324
Well 39	05.7	1900	09.0	17.5	100	10.50	0.50	9.15	1186
Well 29	25.9	1575	15.0	17.5	90	10.40	0.38	9.09	2196

Table 3: Computed coefficients with the use of multiple regression method, trust-region method and proposed scheme for some Khangiran gas field formations

Formation	Mathematical methods	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
Khangiran	Multiple Regression	0.2920	-0.2930	-0.0627	0.2165	-2.406	2.0652	-19.014	-3.625
	Trust-Region	1.0005	0.0002	1.00 e-06	3.87 e-05	1.8354	0.7733	1.1612	0.3000
	GA	1.5348	0.0001	1.16 e-06	9.17 e-05	1.9999	0.9835	0.4864	0.3000
Kalat	Multiple Regression	185.1727	-0.0179	0.0046	0.0149	-0.6338	2.8618	-7.4979	1.8076
	Trust-Region	1.0508	2.09 e-05	0.0004	2.08 e-06	1.5042	0.4894	0.5254	0.3000
	GA	0.8739	6.01 e-05	0.0007	3.04 e-05	1.9999	0.4000	0.30003	0.3001
Abtalkh	Multiple Regression	-3.9644	0.0005	-0.0001	-0.0004	0.9906	0.9113	0.4884	0.0417
	Trust-Region	1.239	1.00 e-06	1.00e-06	1.00e-06	0.8194	0.6794	0.7807	0.3000
	GA	1.3744	1.00 e-06	1.01 e-06	1.00 e-06	1.9999	0.9999	1.4999	0.3000
Shourijeh	Multiple Regression	0.9016	0.0001	-0.0005	0.0000	0.2747	0.3412	-0.4133	0.8126
	Trust-Region	0.9168	0.0003	1.00 e-06	3.01 e-05	1.1828	0.7024	0.5932	0.3003
	GA	0.5000	0.0004	1.04 e-06	6.14 e-06	1.9999	0.9999	0.7147	0.3000
Mozdouran	Multiple Regression	-1.2201	-0.0039	0.0212	0.0020	-21.5217	23.9629	-6.5392	16.4527
	Trust-Region	0.9076	1.00 e-06	1.00 e-06	2.76 e-05	0.5000	0.4000	0.9962	0.3013
	GA	0.5593	1.0013	1.0073	1.0082	0.5000	0.4000	1.3403	0.3000

Table 4: Estimation accuracy of Trust-Region method in comparison with proposed scheme

Formation	Trust-region STD error of estimation	Proposed scheme STD error of estimation	Improvement (%)
Khangiran	5.72	5.48	4.20
Kalat	1.38	1.28	7.20
Abtalkh	1.76	1.33	24.43
Shourijeh	1.05	0.98	6.70
Mozdouran	1.13	1.08	4.40

more efficient than Trust-region method in determining coefficients of Bourgoyne and Young model which leads to more accuracy in drilling rate prediction.

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CONCLUSION

Accurate drilling rate prediction is highly demanded for drilling cost optimization. A simplified model of drilling is called Bourgoyne and Young model, which represents a general mapping between drilling rate and some drilling variables. That model can be used in drilling rate prediction. However, there are eight unknown parameters in this model, which must be determined by using previous drilling experiences. Although, several methods have been suggested to determine these coefficients in last decades, it is hard to reach a predictor system with satisfactory accuracy. In this study we applied GA to determine constant coefficient of Bourgoyne and Young model. Simulation results confirm that suggested approach not only provides meaningful result but also leads to more accuracy in comparison with conventional methods.

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