CSCanada
Advances in Petroleum Exploration and Development
Vol. 8, No. 2, 2014, pp. 58-62
DOI:10.3968/6137

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Application of Gray Analysis Method in Friction Coefficient Assessment for Extended Reach Well

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Supported by National 863 Program "Key Technology Development and Integration for Offshore Extended Reach Well Drilling and Completion" (2012AA091501).

Received 20 October 2014; accepted 25 December 2014
Published online 29 December 2014

Abstract
The friction & torque is a core issue in the process of extended reach well drilling. The friction coefficient has a great influence on friction & torque prediction. Reasonable and correct determination of the friction coefficient is an issue that must be addressed in the friction & torque analysis and prediction. The inverse model of friction coefficient was established based on extensive actual drilling data. On this basis, grey relational analysis is used to explore the potential factors influencing the friction coefficient and establish the association between friction coefficient and the relevant influencing factors. The studying result indicates that the main factors affecting friction coefficient in terms of importance are the average rate of overall angle change, the type of drilling fluid, well depth, hole diameter, drilling fluid density, drilling fluid loss, dynamic shear of drilling fluid, vertical depth, displacement, drilling fluid viscosity, drilling fluid plastic viscosity. The research results can provide a theoretical guide for reducing the friction and torque in the construction of extended reach wells.

Key words: Extended reach well; Friction & torque; Grey relational analysis; Influencing factors; Drilling fluid

Jia, J. H., Yan, Z. L., & Xia, G. Q. (2014). Application of gray analysis method in friction coefficient assessment for extended reach well. *Advances in Petroleum Exploration and Development*, *8*(2), 58-62. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/6137
DOI: http://dx.doi.org/10.3968/6137

INTRODUCTION

In the drilling engineering design and construction process of extended reach well, the prediction and analysis of friction & torque is critical, which is directly related to the success of drilling operation. At present, extensive research on the friction & torque model has been carried out at home and abroad, however, due to the complexity of friction & torque itself, the friction coefficient is often acquired through experience in existing models, the existing model prediction error is big, the torque error even could be more than 50%[1-2]. There are two methods to determine the friction coefficient including laboratory experiments and field data inversion. However, due to the big difference between the indoor simulated conditions and actual drilling conditions, the friction coefficient obtained by the experimental method has a large error and repeatability error, it also exhibits poor stability. This method can only evaluate and optimize the base fluid and lubricant of drilling fluid from one aspect[3-4]. Based on considerable actual drilling data, the author presents a method for the quantitative description on related factors affecting friction coefficient by optimizing the friction & torque calculation models and borrowing from gray system theory on the basis of the inversion of actual drilling friction data. This paper provides the guidance for reducing the friction and torque in the construction of extended reach wells.

1. FRICTION COEFFICIENT INVERSION

1.1 Calculation Model of Friction and Torque

For extended reach well, borehole curvature is generally low. So the drill column can be assumed to be a soft rope which has no flexural rigidity, but could withstand the torque. The soft model is used in the friction & torque calculation model. And the calculation formula is as follows:

$$\begin{cases} N = \left\{ \left[\left(T_1 + T_2 \right) \sin \dfrac{\gamma}{2} + WX \right]^2 + WZ^2 \right\}^{0.5} \\ F = N \cdot f_a \\ T_1 = T_2 + WY \pm F \\ M = 0.5 \cdot N \cdot f_c \cdot D \end{cases} \quad (1)$$

Where:

T_1, T_2 - The axial forces on the up and down cross sections of the string unit, kN;

γ - The dogleg angle of the certain unit, rad;

N - The positive contact force between the drill string unit and the borehole wall, kN;

f_a - Comprehensive friction coefficient, dimensionless;

f_c - Sliding friction coefficient, dimensionless;

F - The frictional resistance of the string unit, kN;

M - Wellhead torque, kN·m;

WX, WY, WZ - Component of the buoyant weight of the string unit on the principle, tangent and the binormal direction, respectively, kN.

1.2 Input Parameters of Friction Coefficient Inversion

In the friction coefficient inversion process, the data to be entered includes: (a) The well trajectory parameters (well depth, inclination, azimuth); (b) The BHA data (the type of drilling tool, grade, outer diameter, inner diameter, unit weight, density, length); (c) The well structure data (well depth, hole diameter); (d) Measured value of hook load during tripping operation (hook load, corresponding depth); (e) The measured torque of rotary table during rotary drilling process (torque of rotary table, corresponding depth); (f) The measured value of hook load during rotary drilling process (the hook load, the corresponding hole depth); (g) The measured value of WOB during rotary drilling (WOB, corresponding depth); (h) The measured value of hook load during slide drilling process (hook load, corresponding depth); (i) The measured value of WOB during slide drilling operation (WOB, corresponding depth); (j) Fluid performance parameters.

1.3 Boundary Conditions of Friction Coefficient Inversion

The friction coefficient between drill string and bore hole, the stress state of drill string and the contact force between drill string and bore hole could be monitored through the measured value of hook load and torque of rotary table during operation. For different drilling conditions, the boundary conditions are as follows:

Tripping Process

$$\left.\begin{aligned} F_t(L) &= 0 \\ M_t(L) &= 0 \\ F_t(0) &= W_{oh} \\ M_t(0) &= 0 \end{aligned}\right\} \quad (2)$$

Where, W_{ob} is Wellhead tension, and T_{ob} is the total length of the drill string.

Drilling Process

$$\left.\begin{aligned} F_t(L) &= -W_{ob} \\ M_t(L) &= T_{ob} \\ F_t(0) &= W_{oh} \\ M_t(0) &= T_{or} \end{aligned}\right\} \quad (3)$$

Where, W_{ob} is the weight on bit, T_{ob} is the drill bit torque.

Rotating off Bottom

$$\left.\begin{aligned} F_t(L) &= 0 \\ M_t(L) &= 0 \\ F_t(0) &= W_{oh} \\ M_t(0) &= T_{or} \end{aligned}\right\} \quad (4)$$

Reaming Process

$$\left.\begin{aligned} F_t(L) &= 0 \\ M_t(L) &= T_{ob} \\ F_t(0) &= W_{oh} \\ M_t(0) &= T_{or} \end{aligned}\right\} \quad (5)$$

Back Reaming Process

$$\left.\begin{aligned} F_t(L) &= 0 \\ M_t(L) &= T_{ob} \\ F_t(0) &= W_{oh} \\ M_t(0) &= T_{or} \end{aligned}\right\} \quad (6)$$

If the friction coefficient is supposed to be an unknown constant in the whole well or a certain hole section, for every measured value of hook load and torque, the friction coefficient could be obtained through the boundary conditions mentioned above.

1.4 The Inversion Process

With tripping out operation, for example, the hook load is F_h, the axial force at drill bit is zero, friction coefficient ranges from 0 to 1, the error excepted (E_{ER}) is 0.02. Detailed calculation is as follows:

(a) Assuming friction coefficient range: $u_{min} = 0$, $u_{max}=1$;

(b) Hook load calculation: Make $u_a = (u_{min} + u_{max})/2$, calculate the hook load F_{bc}, in case $F_{bc} < F_h$, then $u_{min} = u_a$, otherwise $u_{max} = u_a$;

(c) Cyclic iteration to inverse the friction coefficient, if $(u_{max} - u_{min})/u_a > E_{ER}$, return to step (b). Otherwise, u_a is the inversion value of friction coefficient of tripping out.

1.5 Inversion Results of Friction Coefficient

The field data related to extended reach well was collected. Take the rotary drilling for example, the friction coefficient was inverted through iterative approach. During the inversion process, the friction coefficient inside the casing was assumed as 0.2, the iteration step size is 1 m, the friction coefficient at each point in open hole is calculated, and then the average friction coefficient of this well section is obtained. The results are shown in Table 1.

Table 1
Inversion Results of Extended Reach Well Friction Coefficient

Well number	TD (m)	TVD (m)	Displacement (m)	Mud weight (g/cm^3)	Simulation hole section (m)	Average friction coefficient
Bin 173-1HF	3,983	2,892	1,366	1.25	3,607-3,983	0.43
Bin 435-4HF	5,097	3,699	1,786	1.4	4,931-5,097	0.27
Boye-ping 2	3,645	2,568	1,329	1.24	3,332-3,645	0.12
Fan 116-1HF	4,002	2,814	1,405	1.33	3,600-4,002	0.34
Fan 116-2HF	3,912	2,783	1,306	1.32	3,201-3,912	0.35
Fan 116-3HF	4,096	2,789	1,515	1.35	3,844-4,096	0.31
Fan 116-4HF	3,818	2,789	1,187	1.3	3,470-3,818	0.3
Fan 154-7HF	4,260	2,758	1,739	1.38	4,102-4,260	0.47
Fan 154-8HF	4,158	2,761	1,619	1.3	3,786-4,158	0.47
Fan 162-2HF	4,522	2,666	2,066	1.25	4,025-4,522	0.31
Gaoping 1	4,535	948	3,814	1.14	4,200-4,535	0.47
Niu 871-X7	3,752	3,170	1,678	1.51	3,409-3,752	0.19
Xin 14-8HF	4,069	2,582	2,254	1.25	3,852-4,069	0.49
Yan 227-2HF	4,522	3,653	1,345	1.28	4,162-4,522	0.3
Yan 227-5HF	4,740	3,919	1,430	1.25	4,647-4,740	0.29
Yan 227-7HF	4,206	3,411	1,138	1.28	4,069-4,206	0.22
Yan 227-4HF	4,323		1,183	1.28	4,125-4,323	0.36
Yan 227-9HF	4,925	3,841	1,557	1.25	4,206-4,925	0.4
Zhuang 129-1HF	5,341	3,341	3,168	1.4	5,041-5,341	0.21
Liangye 1HF	3,969	3,206	1,010	1.51	3,600-3,969	0.26
Boye-ping 1	4,335	2,969	1,597	1.79	4,100-4,335	0.23

2. CORRELATION ANALYSIS OF INFLUENTIAL FACTORS ON FRICTION COEFFICIENT

2.1 Principles of Gray Correlation Analysis

Grey system theory holds that any random process is a grey variable which changes in a certain range of amplitude value and time. Gray process is done by sorting the raw data to find the law of the number[5].

The basic idea of Grey relational analysis is based on the similarity of geometry curve of each parameter to judge whether the contact is closely related or not, the more similar the shape of the curve, the greater the degree of relevance between the corresponding sequences. The degree of similarity should be described by correlation coefficient and the degree of correlation. The degree of correlation describes how much the factors can influence the results. The bigger the degree of correlation, the greater the degree of influence[6].

For a practical system analysis, the parent factors (a data sequence of system behavior characteristics) and the sub-factors (an effective factors influencing the system behavior characteristics) should be confirmed.

To perform correlation analysis, a reference data column should be specified first. A set of discrete sequence should be required[7-8].

$x_0(k)$, $k = 1, 2, \cdots, m$;

$x_i(k)$, $k = 1, 2, \cdots, m$; $i = 1, 2, \cdots, n$;

$x_0(k)$ is the sequence of parent factors, $x_i(k)$ is a sequence of sub-factors.

The "generation processing" on limited original data in a cumulative way should be carried out before calculation to get more regular data columns. The original sequence of data should be transformed to the dimensionless form in order to maintain dimensional consistency and make all data columns have a point of intersection. Due to the different data dimension, the factors before processing are unable to be compared because the factors with smaller numerical value may be out of action, while the factors with bigger value are exaggerated. Equalization method is commonly used in dimensionless treatment[9-10].

Equalization treatment process is as follows:

$$y_i = \frac{x_i(k)}{\frac{1}{m}\sum_{k=1}^{m} x_i(k)} \quad i = 1, 2, 3 \cdots n,\ k = 1, 2, 3 \cdots, m \tag{7}$$

Where, y_i is the equalization sequence for each factors, $x_i(k)$ is the sequence of sub-factors.

$$y_0 = \frac{x_0(k)}{\frac{1}{m}\sum_{k=1}^{m} x_0(k)} \quad k = 1, 2, 3 \cdots, m \tag{8}$$

Where, y_0 is the equalization sequence for each parent factors, $x_0(k)$ is the parent factor sequence.

The correlation coefficient is calculated as follows,

$$\xi_i(k) = \frac{\min_i \min_k |y_0(k) - y_i(k)| + a \max_i \max_k |y_0(k) - y_i(k)|}{|y_0(k) - y_i(k)| + a \max_i \max_k |y_0(k) - y_i(k)|} \tag{9}$$

Where, ξ_i is the correlation coefficient of y_i on y_0 at k moment, which is the relative difference of reference curve y_0 and comparison curve $y_i(k)$ for i factor at the k point. It is called y_i to y_0 at k point correlation coefficient. It is not convenient to make a comparison if the correlation coefficient is quoted directly because of the large data volume and too dispersive information. It is necessary to convert all the correlation coefficient values at each moment to a single value. Calculating the mean value is a method for processing this information intensively. α is the resolution coefficient, which is generally between 0 and1, usually taken as 0.5。

Grey correlation is calculated as follows:

$$r_i = \frac{1}{N}\sum_{k=1}^{N} \xi_i(k) \quad i = 1,2,3 \cdots n,\ k = 1,2,3 \cdots, m \tag{10}$$

Where, r_i is the correlation degree of Curve y_i to the Reference curve y_0 , the sequence composed of correlation degree r_i describes the influence of sub-factors on parent factors. The correlation degree with bigger value indicates that it has a greater influence on the results.

2.2 Results of Grey Correlation Analysis

Based on the inversion results of friction coefficient (shown in Table 1), the friction coefficient is selected as a parent factor. the well trajectory parameters (including the average dogleg of the full hole, maximum dogleg, difficulty index for orientation), drilling fluid parameters (including drilling fluid density, viscosity, plastic viscosity, dynamic shear force) and the drilling dynamic parameters (including displacement, rotate speed, ROP and dynamic integrated drilling parameters) are selected as the effective factors that affect system behavior characteristics, namely sub-factors.

Based on the Grey relational analysis theory, combined with field actual friction coefficient of basic data (Table 2), several factors influencing on the friction coefficient are analyzed, and the results are shown in Table 3.

Table 2
Basic Data for Grey Correlation Analysis

Well Number	Friction coefficient	Hole size (mm)	Well trajectory parameters				Drilling fluid parameters					
			TD (m)	TVD (m)	Displacement (m)	Average rate of over all angle change (°/30 m)	Drilling fluid type	Density (g/cm^3)	Viscosity (s)	Plastic viscosity (mPa·s)	Dynamic shearforce (Pa)	Fluid loss (ml)
Bin 173-1HF	0.43	215.9	3,983	2,892	1,366	1.19	2	1.25	80	23	14	2
Bin 435-4HF	0.27	215.9	5,097	3,699	1,786	1.4	2	1.4	66	30	14	2.8
Boye-ping2	0.12	215.9	3,645	2,568	1,329	1.19	1	1.25	44	18	9	0.6
Fan 116-1HF	0.34	215.9	4,002	2,814	1,405	1.28	2	1.33	60	35	23	1.2
Fan 116-3HF	0.31	215.9	4,096	2,789	1,515	1.34	2	1.35	147	43	31	1.8
Fan 116-4HF	0.3	215.9	3,818	2,789	1,187	1.2	2	1.3	60	22	14	2
Fan 154-8HF	0.47	152.4	4,158	2,761	1,619	1.3	2	1.3	85	25	16	2.2
Fan 162-2HF	0.31	152.4	4,522	2,666	2,066	1.24	2	1.24	62	20	11.2	1.6
Gao-ping1	0.47	215.9	4,535	948	3,814	1.43	2	1.14	60	22	8.67	2.8
Niu871-X7	0.19	215.9	3,752	3,170	1,678	0.84	2	1.51	60	26	9	4
Xin 14-8HF	0.49	215.9	4,069	2,582	2,254	1.62	2	1.25	63	27	12.5	3.1
Yan 227-2HF	0.3	215.9	4,522	3,653	1,345	0.92	2	1.28	69	28	11.8	1.8
Yan 227-7HF	0.22	215.9	4,206	3,411	1,138	1.06	2	1.28	66	21	9.2	2.6
Yan 227-4HF	0.36	215.9	4,323	3,453	1,183	0.91	2	1.28	66	22	17	2.6
Zhuang 129-1HF	0.21	215.9	5,341	3,341	3,168	0.98	2	1.4	68	26	14	2.4
Boye-ping 1	0.23	215.9	4,335	2,969	1,597	1.03	1	1.75	71	56	13	0.2
Fan 116-2HF	0.35	215.9	3,912	2,783	1,306	1.29	2	1.32	162	26	29	2
Fan 154-7HF	0.47	152.4	4,260	2,758	1,739	1.32	2	1.38	67	33	11	1.8
Yan 227-5HF	0.29	215.9	4,740	3,919	1,430	0.97	2	1.25	55	22	17	2
Yan 227-9HF	0.4	215.9	4,925	3,841	1,557	1.09	2	1.25	60	23	19	3.2
Liangye 1HF	0.26	152.4	3,969	3,206	1,010	0.91	1	1.54	80	36	10	2

Note. In the column of drilling fluid type, "1" means oil-based drilling fluid, "2" means water-based drilling fluid.

Table 3
Grey Correlation Analysis

Factors	Correlation degree	Rank	Factors	Correlation degree	Rank
Hole size (mm)	0.7868	4	Drilling fluid type	0.8552	2
Well depth (m)	0.8324	3	density (g/cm^3)	0.7594	5
TVD (m)	0.6588	8	Viscosity (s)	0.6139	10
Displacement (m)	0.6354	9	Plastic viscosity (mPa·s)	0.6054	11
Average rate of overall angle change (°/30 m)	0.8771	1	Dynamic shear (Pa)	0.7166	7
			Fluid loss (ml)	0.7344	6

Table 3 shows that the main factors affecting the friction coefficient in terms of correlation degree are the average rate of overall angle change, drilling fluid type, well depth, hole size, drilling fluid density, drilling fluid loss, drilling fluid dynamic shear, vertical depth, displacement, drilling fluid viscosity, drilling fluid plastic viscosity. Therefore, in extended reach well drilling process, the smooth well trajectory with low build-up rate should be designed first, followed by a drilling fluid system with good lubricating performance to reduce the friction and torque through the control of drilling fluid performance parameters.

CONCLUSION

(a) The friction in drilling is a concept of hybrid friction including boundary friction, dry friction and fluid friction. So the friction coefficient during drilling operation is a comprehensive friction coefficient influenced by borehole geometry, drilling fluid performance, pipe string structure and the rock properties.

(b) The torque and friction problem is an important research field of the Extended reach well, which runs throughout the entire process of drilling design, drilling operation, well completion operations, etc. The friction coefficient inverted from field actual data shows the consideration on actual drilling condition and has a good reliability. It avoids the limitation of friction coefficient determined by laboratory experiments.

(c) There are many factors affecting the coefficient friction. With the aid of gray correlation analysis theory, the author makes a quantitative description on related factors affecting friction coefficient on the basis of the inversion of friction coefficient. The results show that in extended reach well drilling process, the smooth well trajectory with low build-up rate should be designed first, followed by a drilling fluid system with good lubricating performance to reduce the friction torque through the control of drilling fluid performance parameters.

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