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A numerical method for determining the stuck point in extended reach drilling

Sun Lianzhong and Gao Deli*

Key Laboratory of Petroleum Engineering, Ministry of Education, China University of Petroleum, Beijing 102249, China

Abstract: A stuck drill string results in a major non-productive cost in extended reach drilling engineering. The first step is to determine the depth at which the sticking has occurred. Methods of measurement have been proved useful for determining the stuck points, but these operations take considerable time. As a result of the limitation with the current operational practices, calculation methods are still preferred to estimate the stuck point depth. Current analytical methods do not consider friction and are only valid for vertical rather than extended reach wells. The numerical method is established to take full account of down hole friction, tool joint, upset end of drill pipe, combination drill strings and tubular materials so that it is valid to determine the stuck point in extended reach wells. The pull test, torsion test and combined test of rotation and pulling can be used to determine the stuck point. The results show that down hole friction, tool joint, upset end of drill pipe, tubular sizes and materials have significant effects on the pull length and/or the twist angle of the stuck drill string.

Key words: Extended reach drilling, stuck pipe, torque and drag, numerical method

1 Introduction

In extended reach drilling operations, the stuck pipe has become one of the major non-production incidents (Aadnøy et al, 2003). Pipe sticking dramatically increases the drilling costs which can increase the cost of a development well as much as 30% in offshore operations (Sharif, 1997).

The first step is to determine the depth at which the sticking has occurred (DeGeare et al, 2003). At present, two conventional methods, including measurement and calculation methods, have been used to determine the stuck point. Compared with the calculation method, free-point indicators, acoustic log tools, radial cement bond tools, and other measurement tools can be run down to determine the stuck point or interval with high precision (Russell et al, 2005; Siems and Boudreaux, 2007; Kessler et al, 2010). However, these methods are time-consuming, expensive, and require special instrumentation down to the bottom hole and qualified operators (Whitten, 1990; Aadnøy et al, 2003). As a result of these limitations with the current operational practices the calculation method is still preferred to estimate the depth at the stuck pipe.

The most commonly used method is that stretch in the pipe is measured and a calculation made to estimate the distance to the top of the stuck pipe according to Hooke's Law (DeGeare et al, 2003). The formula neglects wellbore friction and is valid for vertical wells only. In complex wells such as directional wells, horizontal wells, and extended reach wells, this method will produce a large calculation error (Han, 2010). Therefore, scholars are committed to improve methods to consider wellbore friction. Aadnøy et al (2003) considered friction in curved sections and derived equations to estimate the depth to the stuck point in deviated wellbores based on pull tests and torsion tests. However, due to simplifications for torque and drag calculation their accuracy is poor and the methods are applicable only to planned wells rather than actual drilled wells. The method proposed by Han (2010) is based on the premise that the frictions are basically the same when pulling and lowering the drill string to eliminate the impact of friction. But the method is valid only when the axial force of drill string can be effectively transmitted to the stuck point during slackoff, therefore, calculated result is reliable in cases of lower stuck point and smaller drag. Whitten (1990) proposed a method to estimate the position of the stuck point that includes slacking off on the drill string and determining an observed hookload for the drill string during slackoff. This method also faces the same problem whether axial force during slackoff can be transmitted to the stuck point due to drag and buckling in extended reach wells. Even if the axial force can be transmitted to the stuck point, the drill string at the stuck point might be under compression force or tension force of which the value are unknown.

In summary, current analytical methods are based upon the simplifying assumption that either there is no drag or that drag is working everywhere along the drill string in the same direction (Haduch, 1994) and that the axial force can be effectively transmitted to the stuck point. In many cases,

*Corresponding author. email: gaodeli@cup.edu.cn
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this will draw the wrong conclusions. A practical numerical method established in this paper takes full account of friction, tool joint, upset end, combination drill string and drill string materials and is, therefore, valid for extended reach wells.

2 Torque and drag calculations of stuck pipes

During normal operations, drag remains in the same direction as the entire drill string is either moving or stationary. Calculations begin with known forces at the bit, and proceed up the drill string in sequential fashion with torque and drag along the drill string being understood. However, when the drill string becomes stuck, the drill string below the stuck point is stationary which will keep its conditions and forces at the instant of sticking. Though the drill string above the stuck point is free to move, this does not mean that the force applied at surface would be reflected to the stuck point. The force cannot be transmitted to the stuck point until there is the sufficient axial force at every point between the surface and the stuck point which can overcome the maximum friction force. In addition, only hook load and rotary table torque are known, torque and drag calculations begin with the surface down to the stuck point. Therefore, the key to successful estimation of the depth to the stuck point is a clear understanding of the difference of torque and drag calculations between normal operations and pipe sticking (Haduch, 1994).

In extended reach wells torque and drag calculations are much more complicated during slackoff. Therefore, it is not recommended to estimate the position of the stuck point during slackoff. When the stuck point is in the horizontal section, the points above the stuck point may be subjected to compressive load which relates to drill string buckling. Large enough friction may result in helical buckling and lockup of the drill string which make load transmission to the stuck point impossible. Even if the load can be passed to the stuck point, flexural deformation, elongation of the upper, and shortening of the lower part of the drill string make pull length difficult to calculate accurately.

In summary, neither measuring hook load nor deformation during slackoff is the best choice. Only pull tests, torsion tests and combined tests of rotation and pulling are feasible when applied tension and/or torque can be transmitted to the stuck point. As Hooke's Law is valid only in the regime of elastic deformation, pipe failure should be considered to ensure the safety and elastic deformation.

The most important step is to understand the load transmission before determining the depth at the stuck point. On the basis of the model developed by Mitchell and Samuel (2009), a new torque and drag model was developed for various drilling conditions to account for the effects of multiple factors such as pipe stiffness, contact position, and axial and circumferential friction forces.

Neglecting shear deformation, vibration damping, and dynamic effects of the drilling string, the equilibrium of the forces and moments acting on any differential element of a drillstring gives:

$$\begin{cases} \dfrac{\mathrm{d}\boldsymbol{F}}{\mathrm{d}s} + \boldsymbol{w} = 0 \\ \dfrac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}s} + \boldsymbol{t} \times \boldsymbol{F} + \boldsymbol{m} = 0 \end{cases} \tag{1}$$

where $\boldsymbol{F}$ and $\boldsymbol{M}$ are respectively the resultant force vector and moment vector; $\boldsymbol{w}$ is the force per length of drill string; $\boldsymbol{m}$ is the distributed torque per unit length of drillstring.

The force per unit length of drill string $\boldsymbol{w}$ is expressed as:

$$\boldsymbol{w} = \boldsymbol{w}_{\mathrm{bp}} + \boldsymbol{w}_{\mathrm{c}} + \boldsymbol{w}_{\mathrm{d}} \tag{2}$$

$$w_{\mathrm{bp}} = f_{\mathrm{b}} w_{\mathrm{p}} \tag{3}$$

$$f_{\mathrm{b}} = 1 - \frac{\rho_{\mathrm{o}} g A_{\mathrm{o}} - \rho_{\mathrm{i}} g A_{\mathrm{i}}}{w_{\mathrm{p}}} \tag{4}$$

where $\boldsymbol{w}_{\mathrm{bp}}$ is the buoyant weight per unit length of the drill string, N/m; $\boldsymbol{w}_{\mathrm{c}}$ is the contact force per unit length, N/m; $\boldsymbol{w}_{\mathrm{d}}$ is the friction drag force per unit length, N/m; $\boldsymbol{w}_{\mathrm{p}}$ is the weight per unit length of the drill string, N/m; f_{b} is the buoyancy factor; ρ_{o} is the density of the drilling fluid outside the drill string, kg/m^3; ρ_{i} is the density of the drilling fluid in the drill string, kg/m^3; ρ_{s} is the density of the drill string, kg/m^3; A_{o} is outside cross-sectional area of the drill string, m^2; A_{i} is inside cross-sectional area of the drill string, m^2; g is the gravitational acceleration, m/s^2.

Note that $\boldsymbol{w}_{\mathrm{c}}$ lies in the $\boldsymbol{n}$-$\boldsymbol{b}$ plane at angle θ with respect to the $\boldsymbol{n}$ vector, the contact force $\boldsymbol{w}_{\mathrm{c}}$, friction drag force $\boldsymbol{w}_{\mathrm{d}}$ and the distributed torque $\boldsymbol{m}$ per unit length of the drill string are given by:

$$\boldsymbol{w}_{\mathrm{c}} = -w_{\mathrm{c}}(\cos\theta\boldsymbol{n} + \sin\theta\boldsymbol{b}) \tag{5}$$

$$\boldsymbol{w}_{\mathrm{d}} = \mu_{\mathrm{t}} w_{\mathrm{c}}(\sin\theta\boldsymbol{n} - \cos\theta\boldsymbol{b}) - \mu_{\mathrm{d}} w_{\mathrm{c}}\boldsymbol{t} \tag{6}$$

$$\boldsymbol{m} = -\mu_{\mathrm{d}} r_{\mathrm{o}} w_{\mathrm{c}}(\sin\theta\boldsymbol{n} - \cos\theta\boldsymbol{b}) - \mu_{\mathrm{t}} w_{\mathrm{c}} r_{\mathrm{o}}\boldsymbol{t} \tag{7}$$

$$\begin{cases} \mu_{\mathrm{d}} = \pm\mu V \Big/ \sqrt{\left(\dfrac{\pi r_{\mathrm{o}} n}{30}\right)^2 + V^2} \\ \mu_{\mathrm{t}} = \dfrac{1}{30}\mu\pi r_{\mathrm{o}} n \Big/ \sqrt{\left(\dfrac{\pi r_{\mathrm{o}} n}{30}\right)^2 + V^2} \end{cases} \tag{8}$$

where μ is the friction factor; μ_{d} is the axial friction factor and it is positive when the drill string is sliding into the hole and negative while pulling out of the hole; μ_{t} is the circumferential friction factor; $\boldsymbol{t}$, $\boldsymbol{n}$, $\boldsymbol{b}$ are respectively the tangent vector, normal vector, and binormal vector; V is the upward velocity of the drill string, m/s; n is the rotational velocity of the drill string, rpm; r_{o} is the outside radius of the drill string, m.

The drill string is assumed to be an elastic solid material. $\boldsymbol{F}$ and $\boldsymbol{M}$ can be expressed as follows:

$$\boldsymbol{F} = F_{\mathrm{e}}\boldsymbol{t} + F_{\mathrm{n}}\boldsymbol{n} + F_{\mathrm{b}}\boldsymbol{b} \tag{9}$$

$$F_e = F_a + F_{st} = F_a + (p_o + \rho_o v_o^2)A_o - (p_i + \rho_i v_i^2)A_i \tag{10}$$

$$\boldsymbol{M} = EIk\boldsymbol{b} + M_t\boldsymbol{t} \tag{11}$$

where F_e is the effective force, N; F_a is the axial force, N; F_n is the shear force in the normal direction, N; F_b is the shear force in the binormal direction, N; F_{st} is the stream thrust, N; p_o is the annular mud pressure, Pa; p_i is the mud pressure in the drill string, Pa; v_o is the annular mud velocity, m/s; v_i is the mud velocity in the drill string, m/s; M_t is the axial torque, N·m; E is Young's elastic modulus, N/m^2; I is the moment of inertia, m^4; k is the curvature, m^{-1}.

Substituting Eqs. (2) through (11) into Eq. (1) gives:

$$\frac{\mathrm{d}F_e}{\mathrm{d}s} + EIk\frac{\mathrm{d}k}{\mathrm{d}s} + w_{bp}t_z - \mu_d w_c(1 - kr_o\cos\theta) = 0 \tag{12}$$

$$\frac{\mathrm{d}M_t}{\mathrm{d}s} - \mu_t r_o w_c = 0 \tag{13}$$

$$w_c = \frac{\sqrt{(F_e k + \tau^2 EIk + w_{bp}n_z - \tau k M_t)^2}}{\sqrt{1 + \mu_t^2 + \tau^2\mu_d^2 r_o^2 + 2\mu_t\mu_d r_o\tau}} + \frac{\sqrt{\left[w_{bp}b_z - (2\tau EI - M_t)\frac{\mathrm{d}k}{\mathrm{d}s}\right]^2}}{\sqrt{1 + \mu_t^2 + \tau^2\mu_d^2 r_o^2 + 2\mu_t\mu_d r_o\tau}} \tag{14}$$

$$\sin\theta = \frac{w_{bp}b_z - (2\tau EI - M_t)\frac{\mathrm{d}k}{\mathrm{d}s} + w_c\mu_t r_o k}{w_c\left[1 + (\mu_t + \mu_d r_o\tau)^2\right]} - \frac{(\mu_t - \mu_d r_o\tau)(F_e k + \tau^2 EIk + w_{bp}n_z - \tau k M_t)}{w_c\left[1 + (\mu_t + \mu_d r_o\tau)^2\right]} \tag{15}$$

$$\cos\theta = \frac{1}{w_c}(F_e k + \tau^2 EIk + w_{bp}n_z - \tau k M_t + \mu_t w_c\sin\theta - \tau\mu_d w_c r_o\sin\theta) \tag{16}$$

$$F_e(0) = W_{ot} \tag{17}$$

$$M_t(0) = T_{ot} \tag{18}$$

where W_{ot} is the axial tension at the surface, N; T_{ot} is the table torque, N·m; τ is the wellbore torsion, m^{-1}; t_z, n_z, b_z are respectively vertical component of tangent vector, normal vector and binormal vector.

Drill string buckling is an important issue in the torque and drag calculations. Analysis of the critical buckling load can be found in the documents (Cunha, 2004; Mitchell, 2008).

The tangent vector is defined in terms of inclination α and azimuth φ in the following formula:

$$\boldsymbol{t} = (\sin\alpha\cos\varphi, \sin\alpha\sin\varphi, \cos\alpha) \tag{19}$$

With good mathematical properties, spline formulation was used for trajectory calculations to generate continuous well path data. As inclination and azimuth are spline functions of well depth, Frenet formula gives:

$$\begin{cases} t_z = \cos\alpha \\ n_z = \dfrac{\mathrm{d}\alpha}{\mathrm{d}s}\dfrac{\sin\alpha}{k} \\ b_z = -\dfrac{\mathrm{d}\varphi}{\mathrm{d}s}\dfrac{\sin^2\alpha}{k} \end{cases} \tag{20}$$

$$k = \sqrt{\left(\frac{\mathrm{d}\alpha}{\mathrm{d}s}\right)^2 + \sin^2\alpha\left(\frac{\mathrm{d}\varphi}{\mathrm{d}s}\right)^2} \tag{21}$$

$$\frac{\mathrm{d}k}{\mathrm{d}s} = \frac{\dfrac{\mathrm{d}\alpha}{\mathrm{d}s}\dfrac{\mathrm{d}^2\varphi}{\mathrm{d}s^2} + \dfrac{\mathrm{d}\varphi}{\mathrm{d}s}\left(\dfrac{\mathrm{d}\alpha}{\mathrm{d}s}\dfrac{\mathrm{d}\varphi}{\mathrm{d}s}\cos\alpha + \dfrac{\mathrm{d}^2\varphi}{\mathrm{d}s^2}\sin\alpha\right)\sin\alpha}{k} \tag{22}$$

$$\tau = \frac{\sin\alpha\left(\dfrac{\mathrm{d}\alpha}{\mathrm{d}s}\dfrac{\mathrm{d}^2\varphi}{\mathrm{d}s^2} - \dfrac{\mathrm{d}\varphi}{\mathrm{d}s}\dfrac{\mathrm{d}^2\alpha}{\mathrm{d}s^2}\right) + \dfrac{\mathrm{d}\varphi}{\mathrm{d}s}\left[\left(\dfrac{\mathrm{d}\alpha}{\mathrm{d}s}\right)^2 + k^2\right]\cos\alpha}{k^2} \tag{23}$$

A numerical method was used to solve the ordinary differential Eqs. (12-18). The values of the effective axial force, lateral force, torque, contact position angle and other parameters were calculated. As the torque and drag model includes axial and circumferential friction, the computerized model can be applied to drill string analysis under various drilling conditions.

3 Method for determining the stuck point

The pull test is the main method for determining the stuck point in the conventional wells, but it would become difficult to conduct a pull test when the stuck point is deep due to high drag in extended reach wells. The torsion test or combined test of rotation and pulling can be used to determine the stuck point. In this paper, a new numerical method is used to determine the depth to the stuck point.

The initial depth to the stuck point is assumed and the drill string between the surface and the stuck point is then subdivided to n arbitrary different elements. Torque and drag calculations start from the surface down to the stuck point with the finite difference method and then it is determined whether the tension and/or table torque can be transmitted to the stuck point. If it can be done, force increment and deformation of any differential element are then calculated. The pull length and/or twist angle will be determined by cumulative calculation. Comparison is made between the calculated and observed pull length and/or twist angle. The stuck point estimation and comparison steps are repeated until the calculated pull length and/or twist angle agrees with the measured value within a predetermined tolerance. Figs. 1 and 2 give the idealized flow charts of the computer program for the pull test and the torsion test which are similar to the combined pull and rotation test.

Since steel behaves as linearly elastic, any differential element i of the drill string under tension and/or torsion follows Hooke's law. The elongation or the angle of rotation becomes:

$$\mathrm{d}L_i = \frac{L_i\,\mathrm{d}F_i}{E_i A_i} \tag{24}$$

$$\mathrm{d}\iota_i = \frac{L_i\,\mathrm{d}M_i}{G_i J_i} \tag{25}$$

$$G = \frac{E}{2(1+\nu)} \tag{26}$$

$$J = \frac{\pi}{32}(d_\mathrm{o}^4 - d_\mathrm{i}^4) \tag{27}$$

The pull length and twist angle are respectively the accumulation of the elongation and the angle of rotation of all differential elements.

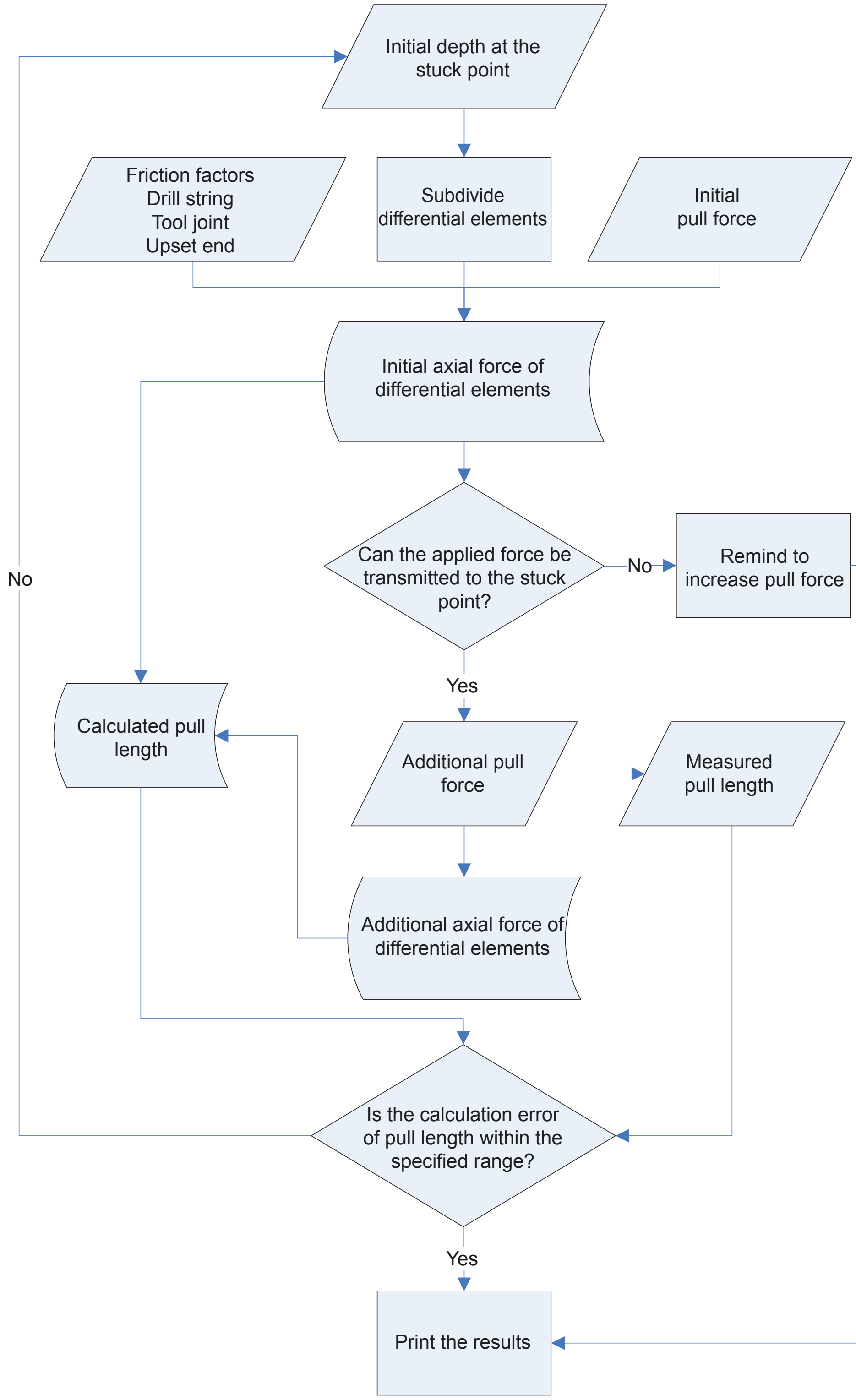

Fig. 1 Flow chart for determining the stuck point by the pull test

$$\mathrm{d}L = \sum_{i=0}^{n} \frac{L_i}{E_i A_i} \mathrm{d}F_i \tag{28}$$

$$\mathrm{d}\iota = \sum_{i=0}^{n} \frac{L_i}{G_i J_i} \mathrm{d}M_i \tag{29}$$

where L is the length of the drill string, m; F is the applied pull force, N; M is the applied torque, N·m; ι is the rotation of the drill string, degrees; G is the shear modulus, m^4; J is the polar moment, m^4; v is the Poisson's ratio; d_o is the outside diameter (OD) of the drill string, m; d_i is the inside diameter (ID) of the drill string, m.

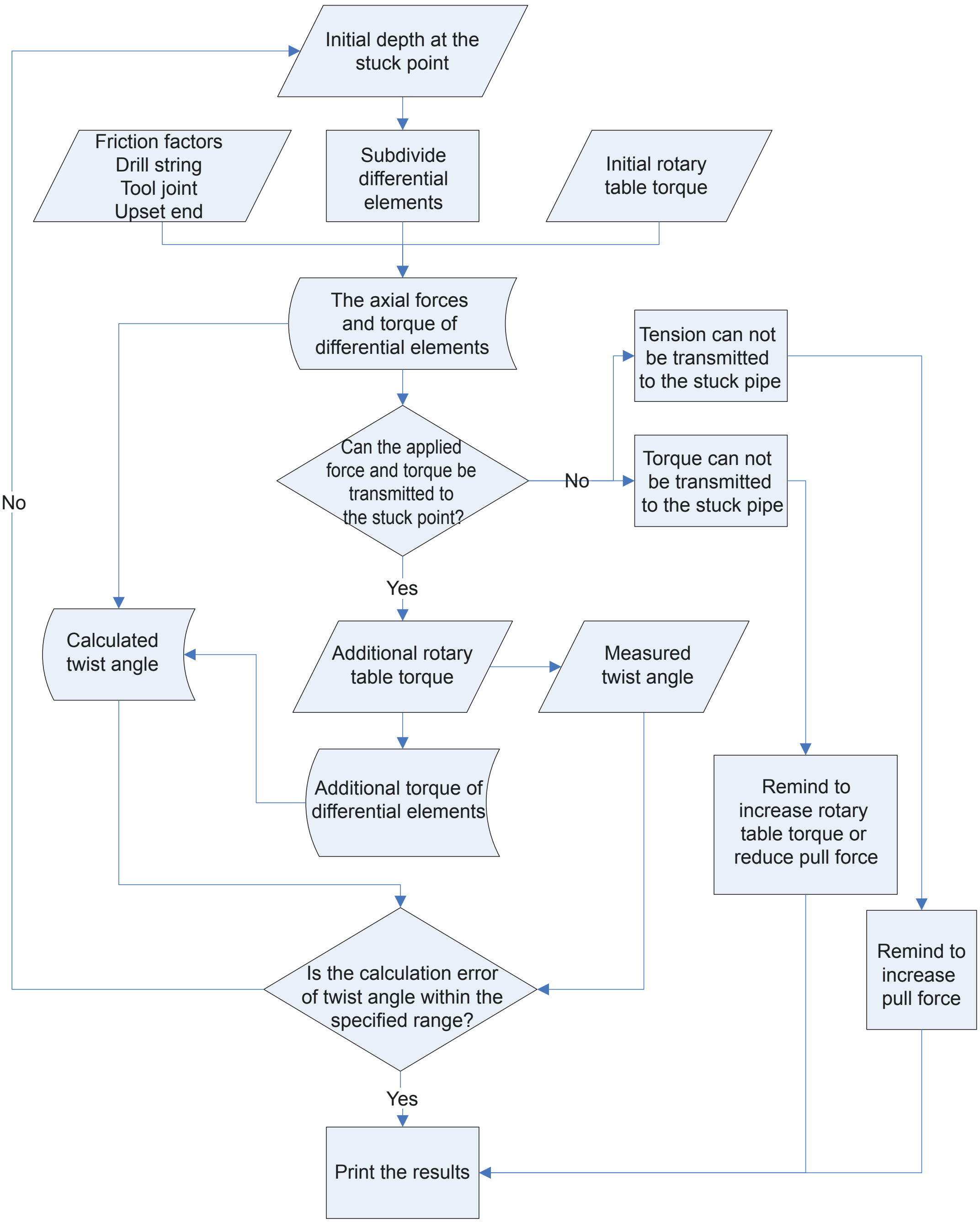

Fig. 2 Flow chart for determining the stuck point by the torsion test

4 Discussion

The data of well LH11-1-D4PH were used to investigate the influence of various factors on the stuck point prediction. Well LH11-1-D4PH is a long openhole extended-reach well in the Liuhua 11-1 Oilfield in the South China Sea. The well profile of well LH11-1-D4PH is shown as Fig. 3 and the data of drill pipes, tool joint and the upset end are shown in Tables 1 and 2.

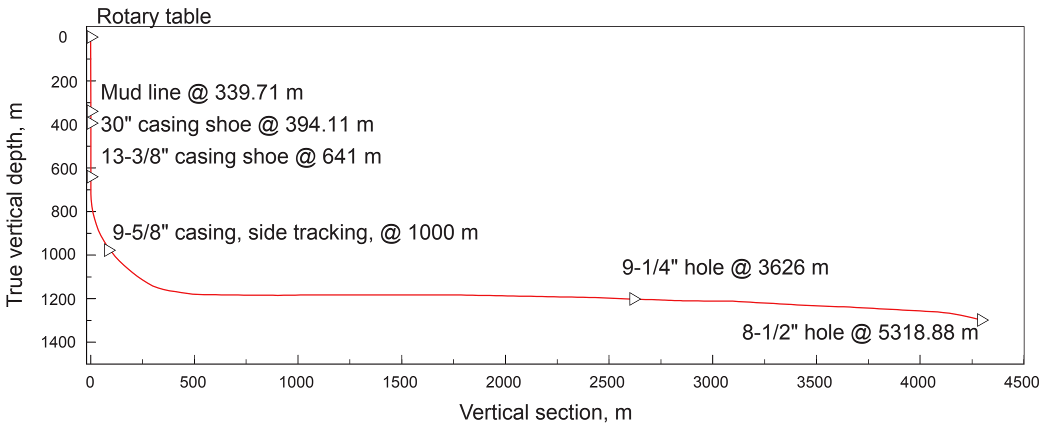

Fig. 3 Well trajectory profile of well LH11-1-D4PH

Table 1 Drill pipes for the calculations

Drill pipe	OD mm	ID mm	Weight per unit length, N/m	*E* N/m^2	*v*
5-7/8" ADP	149.20	120.70	226.05	7.00×10^{10}	0.33
5-1/2" DP	139.70	121.40	319.38	2.06×10^{11}	0.30

Table 2 Data of the tool joint and upset end for 5-1/2" drill pipe

Tool joint			Upset end		
OD mm	ID mm	Length mm	OD mm	ID mm	Length mm
177.80	101.60	457.00	141.30	96.90	107.95

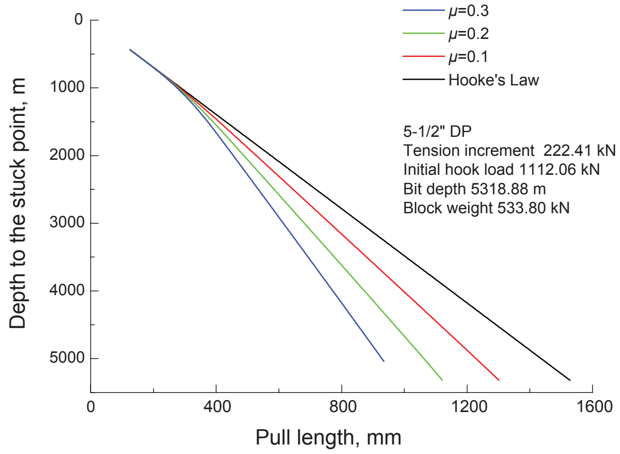

Fig. 4 The influence of drag on pull length while pulling

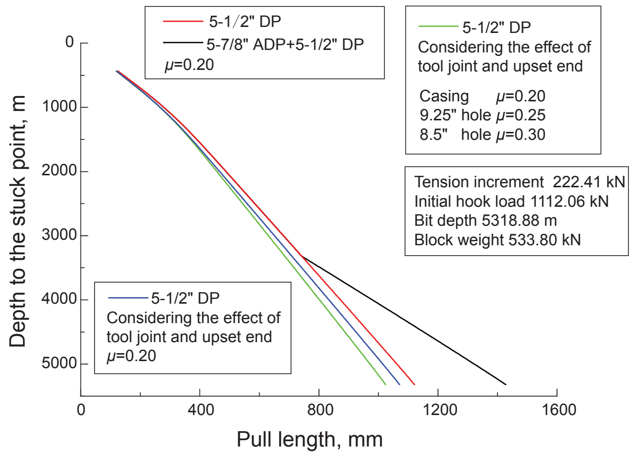

Fig. 5 The influence of drag, material, tool joint and upset end on pull length while pulling

Fig. 4 shows the relationship between the pull length and the depth to the stuck point when 5-1/2" drill pipe (DP) is being pulled. It can be seen that drag has a great impact on the pull length, and the greater the friction factor, the smaller the pull length. As is shown in Fig. 5, when the impact of tool joint and upset end is considered, the pull length becomes smaller and the stuck point appears deeper. When the pull length is the same, the stuck point is the lowest when calculated from Hooke's law, which could explain why the measured depth to the stuck point is always higher by hundreds of meters than the calculated value from Hooke's law. In addition, applications of Hooke's law do not determine whether or not the pull force can be passed to the stuck point, which would increase the calculation error. As shown in Fig. 4, when the friction factor is 0.3 and the hook load increases from 1,112.06 to 1,334.47 kN, the relation curve between the pull length and the depth is only extended to 5,038 m. In this case the pull force will not be transmitted to the stuck point if the depth to the stuck point is beyond 5,038 m.

There are different friction factors in different sections even in the same section in extended reach wells. In order to improve calculation accuracy, friction factors are recommended for stuck point calculations and the closer to the actual friction factors the more reliable calculated depth to the stuck point (see Fig. 5).

Figs. 5 and 6 analyze the effect of materials on the pull length and twist angle. Under the same conditions, using 2,000 m aluminum drill pipe (ADP) will make the pull length and twist angle become larger because of smaller Young's modulus of the aluminum drill string.

As shown in Fig. 7, the influence of hook load and friction on twist angle are analyzed for torsion. Under the same hook load and table torques, the relation curve between twist

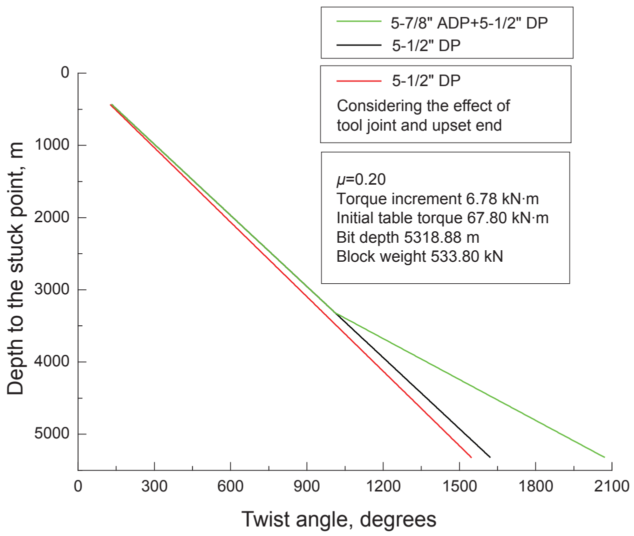

Fig. 6 The influence of material, tool joint and upset end on twist angle while rotating

angle and depth to the stuck point will be slightly affected by friction factors. The difference is that the table torque would not be delivered to the stuck point when the friction factor and the depth to the stuck point are larger. In general, the values of friction factor are known in the drilled well. Under the same friction factor and table torque the relation curve between the twist angle and the depth to the stuck point will also be slightly affected by hook loads. However, larger hook load and deeper stuck point lead to larger torque loss, which may result in the table torque may not be delivered to the stuck point. In both the above cases, the influence of the hook load and the friction factor on the twist angle are negligible. The main reason is that there is nearly no drag in the axial direction while rotating drill string, which makes the lateral forces unchanged. As long as the table torque can be passed to the stuck point, the torque increment at the stuck point would be the same as that at the table, which means the torque increment can be transmitted to the stuck point effectively.

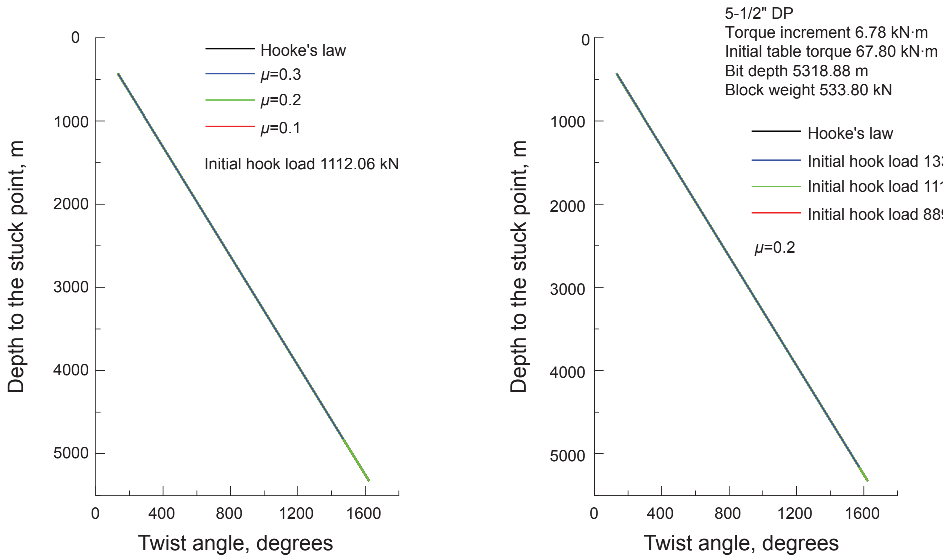

Fig. 7 The influence of friction and hook load on twist angle while rotating

Fig. 6 shows the influence of the tool joint and the upset end on twist angle. If the effect is ignored, the calculated twist angle or pull length will be about 5% larger whether for torsion tests or pull tests in extended reach wells (see Fig. 8). Zhou et al (2010) carried out torsion tests for stuck steel pipe in horizontal wells, and the result shows that the friction had little effect on the twist angle and the twist angle is mainly affected by torque increment, tool joint and upset end, which is consistent with the calculation of this paper.

Due to large drag in extended reach wells the hook load required for sliding out of hole would exceed the maximum rig lifting capacity. The combined pulling and rotation test can be used to reduce the drag and determine the stuck point. As shown in Fig. 9, the friction affects both the pull length and the torsion angle for the combined pulling and rotation test. The greater the friction factor, the smaller the pull length and the torsion angle. Compared with pull tests, rotating the drill string will dramatically reduce the axial drag and the

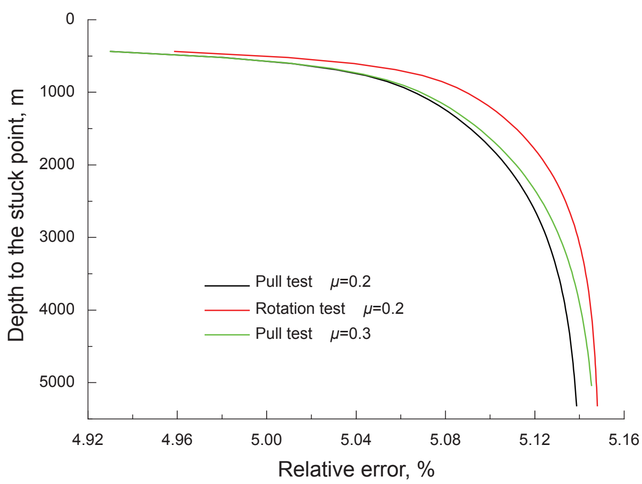

Fig. 8 The influence of tool joint and upset end on twist angle and pull length

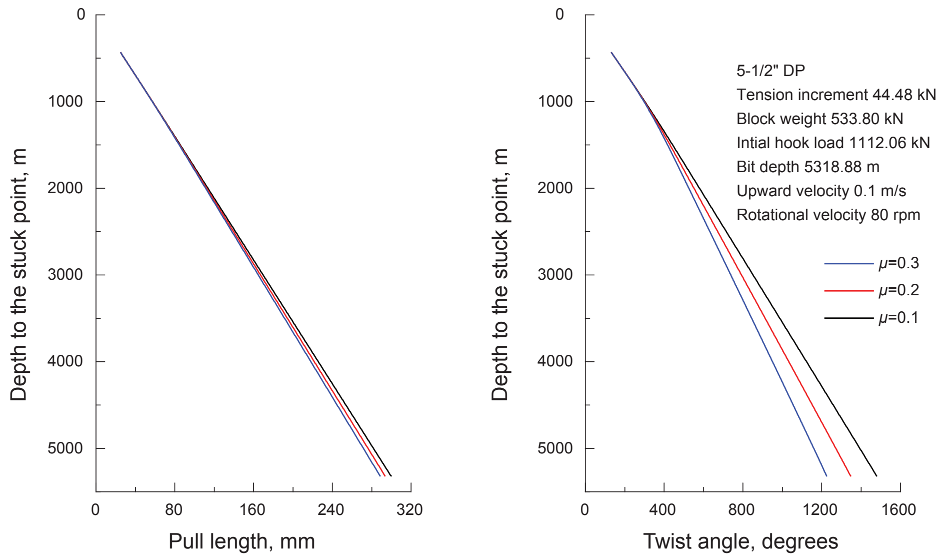

Fig. 9 The influence of friction on twist angle and pull length while pulling and rotating

effect of the friction factor on the pull length. Compared with torsion tests, the axial tension and lateral force will become larger after the combined pulling and rotation test, which will result in a decrease in the torque increment with an increase in the measured depth and the friction factor. The greater the friction factor, the smaller the torsion angle.

5 Conclusions

A new method was developed to determine the stuck point. On the basis of case studies, the following conclusions are drawn:

1) Drag has a significant impact on the pull length while pulling the stuck drill string. The greater the friction factor, the smaller the pull length.

2) Effects of the hook load and the friction on the twist angle are negligible while rotating the stuck drill string.

3) The friction factor has a more significant effect on the twist angle than the pull length while pulling and rotating the stuck drill string. The greater the friction factor, the smaller the torsion angle and the pull length.

4) Due to the tool joint and the upset end, the stuck point calculated is deeper. When the effects are taken into considerations, the pull length or the twist angle calculated is smaller about 5%.

5) Compared with the pull tests, the application of Hooke's law to torsion tests may obtain the stuck point depth with higher accuracy as if the applied force at the surface can be transmitted to the stuck point.

6) The numerical method established in this paper takes full account of the down hole friction, the tool joint, the upset end of drill pipe, tubular materials and sizes, that is valid for determining the stuck point in extended reach drilling.

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