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The Effects of Borehole Ovality on Bare Hole Horizontal Well Completion String Tripping in Friction

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Abstract
Under the effect of non-uniform ground stress, the borehole becomes oval. The deformation regulations and friction calculation in oval borehole has great difference with which in circular borehole. Researching the effect of the ovality of borehole on string tripping in friction is of great significance. In this paper, the string deformation model in oval borehole was established; the maximum displacement changes with different ratios of the major and minor axis and inclination angles were analyzed. The deformation model between two contacting points was established, and the determining method of the new contacting point of multi-packer completion string was proposed. The friction calculating model was established finally.The Hongping 9 well was used as an example to calculate the effect of borehole ovality on the bare hole completion string tripping in friction. By calculating, the friction calculated using the model was in good agreement with the measured value. The friction of completion string is almost zero in vertical section, and in blending and horizontal section the friction is increasing gradually. With the increasing of ovality the friction is increasing. The ovality increases from 1.0 to 1.3, the increasing value of friction is 36.59 kN.

Key words: Borehole ovality; Completion string; Bare hole completion; Friction

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INTRODUCTION
Horizontal well multistage fracturing is an effective measurement to enhance the deliverability of tight sand reservoir, and it is widely used in oil fields[1-3]. Horizontal well bare hole packer completion string tripping in smoothly is the prerequisite of multistage extensive fracturing construction using packers and scale sleeves in long naked horizontal section[4-6]. Many scholars at home and abroad have done a lot of work for predicting and analyzing horizontal well completion string tripping in friction. Johancsik[7] proposed a mathematical model for calculating torque and friction of the string (soft rod model), and he attributed string friction and torque to the result of simple sliding friction generated by the contact between string and the borehole wall. Ho HS[8] established the revised soft rod model according to large deformation mechanical analysis of drill string. Dr. Hualin Liao[9] established the model of calculating string friction considering two different situations that the string has and has not installed centralizers. Ying'an Zhang[10] established mechanical model of the string between packers for horizontal well fracturing string, and obtained the deformation characteristic of the string between packers. Although some scholars have studied the string deformation characteristic, and established string friction calculation model, the effect of the ovality of borehole on string tripping in friction has not been studied. Under the effect of non-uniform ground stress, the borehole becomes oval, and researching the effect of the ovality of borehole on string tripping in friction is of great

significance. In this paper, the issue has been studied in theory, which is a supplement for studying completion string tripping in friction.

1. THE DEFORMATION ANALYSIS OF COMPLETION STRING IN OVAL BOREHOLE

Under the effect of non-uniform ground stress, the borehole becomes oval. The angle between the major axis of oval borehole and horizon plane is θ. The cross-section shape of borehole and position of string can be shown in Figure 1.

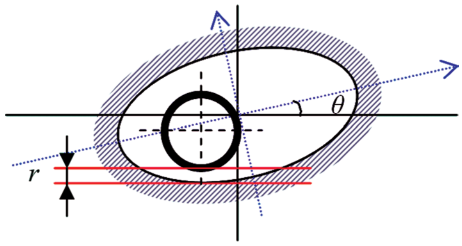

Figure 1
The Cross-Section Shape of Borehole and the Position of String

The major axis of the borehole is x-axis and the minor axis is y-axis, and the plane coordinate system is established. The center of the string is above the lowest point of the wellbore, and the straight line equation goes through the lowest point can be shown as follow.

$$y = -\tan\theta\, x + c \tag{1}$$

The equation for calculating the intersection point coordinates of the line and ellipse can be shown as follow.

$$\frac{x^2}{a^2} + \frac{\tan^2\theta\, x^2 + c^2 - 2c\tan\theta\, x}{b^2} = 1 \tag{2}$$

Where: a is the length of minor semi-axis; b is the length of major semi-axis.

Assume that δ is the ratio between the length of major and minor semi-axis. The a and b variables can be shown as follow.

$$b = \frac{D}{\delta+1},\ a = \frac{\delta D}{\delta+1} \tag{3}$$

The line is tangent to the ellipse, and only has an intersection point. By deriving, the coordinate of the lowest point of ellipse is shown as follow.

$$(x_0, y_0) = \left(-\frac{\delta^2 \tan\theta}{(\delta+1)\sqrt{1+\delta^2\tan^2\theta}} D, -\frac{1}{(\delta+1)\sqrt{1+\delta^2\tan^2\theta}} D \right) \tag{4}$$

where: x_0, y_0 are the x-coordinate and y-coordinate of the lowest point respectively.

According to the geometric relationship between string and borehole, the coordinate of the string center can be obtained as follow.

$$(x_c, y_c) = (x_0 + r_f \sin\theta, y_0 + r_f\cos\theta)$$

Where: x_c, y_c are the x-coordinate and y-coordinate of the string center respectively; r_f is the packers outside diameter of completion string.

In order to calculate the displacement amount in each direction before the string contacts with borehole wall, assuming that the straight line with α gradient goes through the center of the string, the equation of the straight line is:

$$y = \tan\alpha x - \tan\alpha x_c + y_c \tag{5}$$

The two intersection point coordinates can be obtained according to the equation of the line and ellipse.

The upper intersection point:

$$(x_u, y_u) = \left(\frac{-B_f + \sqrt{B_f^2 - 4A_fC_f}}{2A_f}, \tan\alpha\left(\frac{-B_f + \sqrt{B_f^2 - 4A_fC_f}}{2A_f} - x_c \right) + y_c \right)$$

The lower intersection point:

$$(x_d, y_d) = \left(\frac{-B_f - \sqrt{B_f^2 - 4A_fC_f}}{2A_f}, \tan\alpha\left(\frac{-B_f - \sqrt{B_f^2 - 4A_fC_f}}{2A_f} - x_c \right) + y_c \right)$$

Where: $A_f = b^2 + a^2\tan^2\alpha = \dfrac{D^2\left(1+\delta^2\tan^2\alpha\right)}{(\delta+1)^2}$

$$B_f = 2a^2\tan\alpha\left(y_c - \tan\alpha x_c\right) = \frac{2\delta^2 D^2\tan\alpha\left(y_c - \tan\alpha x_c\right)}{(\delta+1)^2}$$

$$C_f = a^2\left(y_c - \tan\alpha x_c\right)^2 - a^2b^2 = \frac{\delta^2 D^2\left[\left(y_c - \tan\alpha x_c\right)^2(\delta+1)^2 - D^2\right]}{(\delta+1)^4}$$

The moving distance of the string at any angle can be obtained by deriving the geometric relationship.

$$d_l(\alpha_0)=\begin{cases}\sqrt{\left[x_u(\alpha+\theta)-x_c\right]^2+\left[y_u(\alpha+\theta)-y_c\right]^2} & -\theta\le\alpha<\pi-\theta\\ \sqrt{\left[x_d(\alpha+\theta)-x_c\right]^2+\left[y_d(\alpha+\theta)-y_c\right]^2} & -\theta\pi\le\alpha<2\pi-\theta\end{cases}\tag{6}$$

where: α is the angle between any direction and oval borehole major semi-axis direction; α_0 is the angle between any direction and horizontal direction.

Because of the well track variations, the declination angle θ is different at different positions on well track, and it is necessary to transform the coordinate in original system to unified system. The old and new coordinate system coordinates conversion formula is:

$$\begin{bmatrix}x'\\ y'\end{bmatrix}=\begin{bmatrix}x\\ y\end{bmatrix}\begin{bmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{bmatrix}\tag{7}$$

By calculating, the maximum displacement changes with the direction of the string at different δ can be shown in Figure 2. When δ is 1.2, the maximum displacement changes with different ellipse inclination angles can be shown in Figure 3. When δ is different, with the increasing of the ovality, the maximum value of the maximum displacement is increasing, and the minimum becomes decreasing. When ellipse inclination angle is different, the maximum displacement changes according to sine law with the direction of string, and the increasing amount of ellipse inclination angle is the amount that the curve moves to the left.

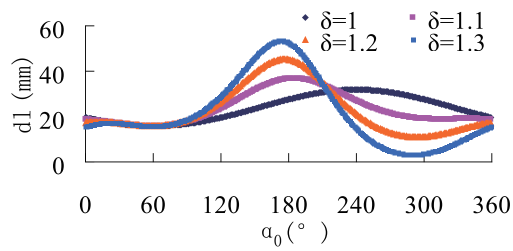

Figure 2
The Maximum Displacement Changes with the Direction of the String at Different δ

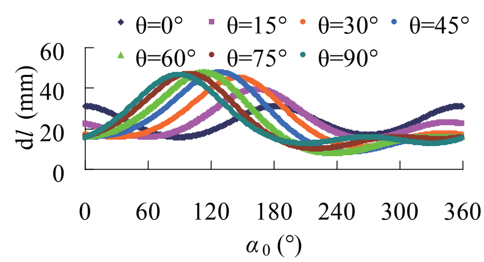

Figure 3
The Maximum Displacement Changes with the Direction of the String at Different Ellipse Inclination Angles of Bolehole

2. THE FRICTION CALCULATING MODEL DURING COMPLETION STRING TRIPPING IN

2.1 The Deformation Model Between Two Contacting Points

The two arbitrary adjacent contacting points (i, i+1) of completion string and borehole wall in three-dimensional borehole is shown in Figure 4. A point is fixed simply supported, and B is active simply supported. Assuming that x direction is the direction of the line between the two points, and y direction is the direction that is vertical to x-axis and coplanar with the direction of gravity. The angle between x-axis and the horizontal plane is α.

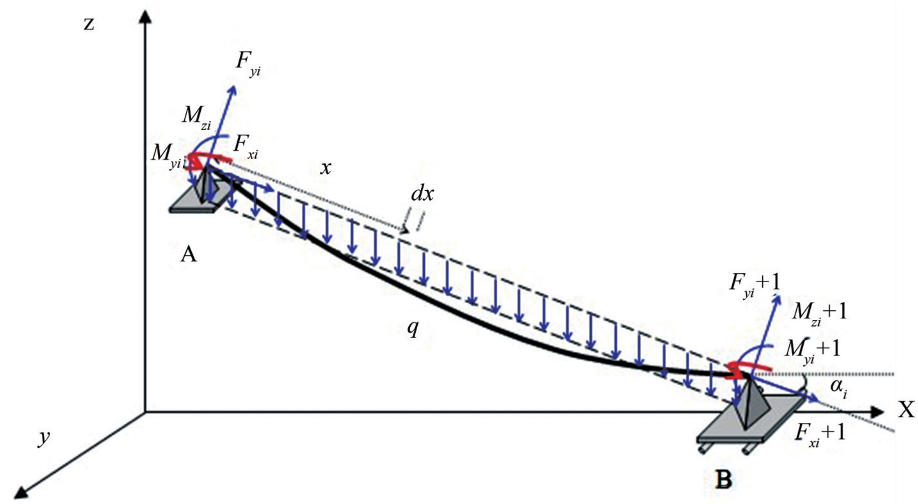

Figure 4
The Deformation Model Between Two Contacting Points of the Completion String

The supporting force of x, y, z direction loading on i point are F_{xi}, F_{yi}, F_{zi} respectively. The shaft torque of y-axis and z-axis loading on i point are M_{zi}, M_{zi+1} respectively. The string bending moment equation is obtained according to force and moment equilibrium equation.

$$M(x) = -F_{xi}\omega - \frac{q\sin\alpha}{2}\omega x + \left(\frac{lq\cos\alpha}{2} + \frac{M_{zi+1}-M_{zi}}{l}\right)x - \frac{q\cos\alpha}{2}x^2 + M_{zi} \tag{8}$$

The completion string between two points is at the state of slightly bent equilibrium, and equation of deflection curve ($\omega=\omega(x)$) of the string satisfy the following relationship:

$$\frac{d^2\omega}{dx^2} = \frac{M(x)}{EI} \tag{9}$$

The equation of deflection curve of the string can be obtained by substituting Equation 8 into Equation 9.

$$\frac{d^2\omega}{dx^2} = \frac{1}{EI}\left[-F_{xi}\omega - \frac{1}{2}q\sin(\alpha)\omega x + \left(\frac{1}{2}q\cos\alpha + \frac{M_{zi+1}-M_{zi}}{l}\right)x - \frac{q\cos\alpha}{2}x^2 + M_{zi}\right] \tag{10}$$

The equation of deflection curve general solution of the string at y-axis can be obtained by solving Equation 10.

$$\omega_{yi}(x) = C_1\cos\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + C_2\sin\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + \frac{1}{F_{xi}}\left[\frac{q\cos\alpha}{F_{xi}}EI + M_{zi} + \left(\frac{lq\cos\alpha}{2} + \frac{M_{zi+1}-M_{zi}}{l}\right)x - \frac{q\cos\alpha}{2}x^2\right] \tag{11}$$

In the same way, the displacement equation at z-axis can be expressed:

$$\omega_{zi}(x) = C_3\cos\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + C_4\sin\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + \frac{1}{F_{xi}}\left(M_{zi} + \frac{M_{yi+1}-M_{yi}}{l}x - \frac{q\cos\alpha}{2}x^2\right) \tag{12}$$

Differentiating Equation 11 and Equation 12, the angle of twist of the string can be expressed as follow.

$$\theta_{yi}(x) = C_5\sqrt{\frac{F_{xi}}{EI}}\cos\left(\sqrt{\frac{F_{xi}}{EI}}x\right) - C_6\sqrt{\frac{F_{xi}}{EI}}\sin\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + \frac{1}{F_{xi}}\left[\frac{lq\cos\alpha}{2} + \frac{M_{zi+1}-M_{zi}}{l} - (q\cos\alpha)x\right] \tag{13}$$

$$\theta_{zi}(x) = C_7\sqrt{\frac{F_{xi}}{EI}}\cos\left(\sqrt{\frac{F_{xi}}{EI}}x\right) - C_8\sqrt{\frac{F_{xi}}{EI}}\sin\left(\sqrt{\frac{F_{xi}}{EI}}x\right) + \frac{M_{yi+1}-M_{yi}}{F_{xi}l} \tag{14}$$

2.2 The Determining Method of the New Contacting Point of Multi-Packer Completion String

2.2.1 The Determining Method of the New Contacting Point when the Packers Are in the Bending Section

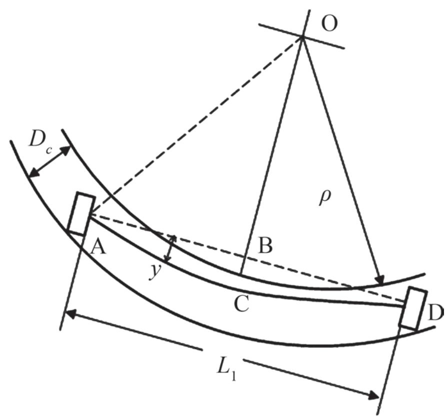

Figure 5
The Deformation of String in Blending Section

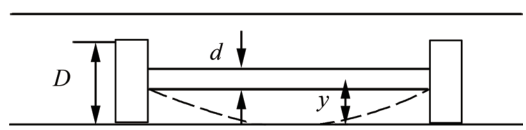

Figure 6
The Deformation of String in Horizontal Section

When the packers are in bending section, the deformation of string can be shown in Figure 5. The deflection curve of the string between two packers is AD, and y is deflection of the curve at any point. L_1 is the distance between the two packers. According to the geometry relationship, it can show that:

$$L_{BC} = \rho - \sqrt{(\rho + \frac{D_c}{2})^2 - (\frac{L_1}{2})^2} \tag{15}$$

When the string contacts with the top of casing, it can be shown as follow.

$$y_{\max} < L_{BC} \tag{16}$$

When the string contacts with the bottom of casing, it can be shown as follow.

$$y_{\max} > L_{BC} + D_c \tag{17}$$

2.2.2 The Determining Method of the New Contacting Point when the Packers Are in the Horizontal Section

When the packers are in horizontal section, the deformation of string can be shown in Figure 6. According to the geometry relationship, the critical condition that the string between two packers contacts with the inside wall of the casing can be shown as follow.

$$y_{\max} < \frac{1}{2}(D-d) \tag{18}$$

Where: $y_{\max}$ is the maximum deflection of the string, m; D is the outside diameter of packer, m; d is the outside diameter of string, m;

2.3 The Friction Model of Horizontal Well Bare Hole Completion String

2.3.1 The Friction Model of Completion String in Vertical Section

The axial force of the string is less than the critical deformation load in vertical section, and the string does not have contacting friction. The friction of the completion string is 0.

$$F_i = 0 \tag{19}$$

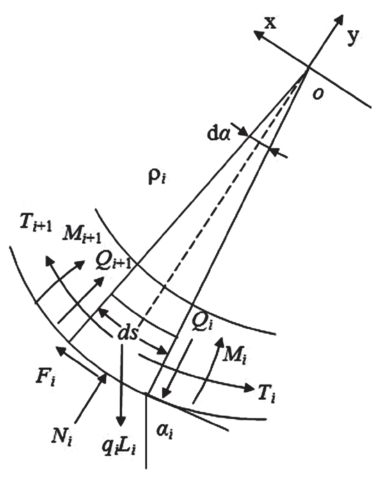

Figure 7
The Model for Calculating Friction in Bending Section

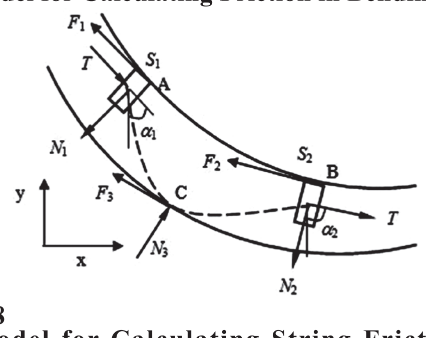

Figure 8
The Model for Calculating String Friction with Packers in the Bending Section

2.3.2 The Friction Model of Completion String in Bending Section

(1) The friction model of completion string without packers in bending section

When the string is in the bending section, because of the bending of borehole, the string has a certain initial bending. Take the micro unit of completion string in bending section for stress analysis, and it is shown in Figure 7. The recurrence relationship can be obtained according to the static equilibrium equations at x-direction and y direction, moment equilibrium equation (the supported point is base point), and bending moment calculation equation.

$$F_i = \frac{\mu_i}{A}\left(2T_i tg\frac{\Delta\alpha}{2}\sin\frac{\Delta\alpha}{2} - 2Q_i\sin\frac{\Delta\alpha}{2} - \frac{(M_{i+1}-M_i)}{\rho_i\cos\frac{\Delta\alpha}{2}} - Bq_iL_i\right) \tag{20}$$

$$T_{i+1} = q_iL_i\cos(\alpha_i - \frac{\Delta\alpha}{2}) - \mu_iN_i - \frac{M_{i+1}-M_i}{\rho_i} + T_i \tag{21}$$

$$Q_{i+1} = q_iL_i\frac{\sin(\alpha_i-\frac{\Delta\alpha}{2}) - \cos(\alpha_i-\frac{\Delta\alpha}{2})\sin\frac{\Delta\alpha}{2}}{\cos\frac{\Delta\alpha}{2}} + N_i\frac{\mu_i\sin\frac{\Delta\alpha}{2}-1}{\cos\frac{\Delta\alpha}{2}} + \frac{M_{i+1}-M_i}{\rho_i}tg\frac{\Delta\alpha}{2} - 2T_i tg\frac{\Delta\alpha}{2} + Q_i \tag{22}$$

Where: $A = \mu_i\frac{1-\cos\frac{\Delta\alpha}{2}}{\cos\frac{\Delta\alpha}{2}} - tg\frac{\Delta\alpha}{2}$;

$$B = \frac{\sin(\alpha_i-\frac{\Delta\alpha}{2})\sin\frac{\Delta\alpha}{2} + \cos(\alpha_i-\frac{\Delta\alpha}{2})\cdot(\cos\frac{\Delta\alpha}{2}-1)}{\cos\frac{\Delta\alpha}{2}};$$

q_i is the weight per unit length of string, N; L_i is the i-th unit string length, m; Q_i is the shear force caused by string blending of the i-th unit, N; T_i is the axial force of the i-th unit, N; F_i is the friction of the i-th unit, N.

Equations (20), (21), (22) are the recurrence relational expression. The friction of the string can be obtained according to the recurrence relation and the initial conditions, using stepwise superposition method. The friction of the completion string in blending section can be expressed as follow.

$$F = \sum_{i=1}^{n} F_i \tag{23}$$

(2) The friction model of completion string with packers in bending section

The string between packers can occur flexural deformation under the axial force. When the string deformation reaches the limit changes of the string bending deflection in casing string, string and the casing inside wall generates new contacting point, which is shown in Figure 8. The packers (S_1 and S_2) are under effect of axial force (T), and the new contacting point is C. According to the static equilibrium equation of the string in blending section, the equation can be obtained as follow.

$$\begin{cases} T\cos\alpha_1 = F_1\cos\alpha_1 + N_1\sin\alpha_1 - N_3\cos\alpha_3 + F_3\sin\alpha_3 + F_2\cos\alpha_2 + T\cos\alpha_2 + N_2\sin\alpha_2 \\ T\sin\alpha_1 = F_1\sin\alpha_1 - N_1\cos\alpha_1 + N_3\sin\alpha_3 + F_3\cos\alpha_3 - N_2\cos\alpha_2 - F_2\sin\alpha_2 - F_3\sin\alpha_2 \end{cases} \tag{24}$$

Taking moments on A and B, according to moment equilibrium equation, the supporting force N_1 imposed on packer S_1 from casing can be obtained by solving.

$$N_1 = \frac{(ab + 1 + \mu b)\cos\alpha_2 + (a+b)\sin\alpha_2 + b\sin\alpha_2}{c(\cos\alpha_1 - a) + \mu(a\sin\alpha_1 - \cos\alpha_1) - a\cos\alpha_1} T \tag{25}$$

The supporting force N_2 imposed on packer S_2 from casing can be expressed:

$$N_2 = \frac{L\sin\alpha_2}{L\cos\alpha_2 - \mu(L\sin\alpha_2 + D_F)} T \tag{26}$$

The supporting force N_3 imposed on the contacting point can be expressed:

$$N_3 = \frac{(\mathrm{a}+\mathrm{b})\sin\alpha_3 + b(a + \sin\alpha_2)}{\mu(a\cos\alpha_3 + b\cos\alpha_1)} T \tag{27}$$

The friction of packer S_1, S_2 and the contacting point can be expressed:

$$F_i = \mu N_i \qquad i = 1, 2, 3 \tag{28}$$

Where: $a = \dfrac{\mu\sin\alpha_3 - \cos\alpha_3}{\mu\cos\alpha_3 + \sin\alpha_3}$;

$$b = \frac{L\sin\alpha_2}{L\cos\alpha_2 - \mu(L\sin\alpha_2 + D_F)}$$

$$c = \frac{L\sin\alpha_1}{L\cos\alpha_1 - \mu(L\sin\alpha_1 + D_F)}$$

2.3.3 The Friction Model of Completion String in Horizontal Section

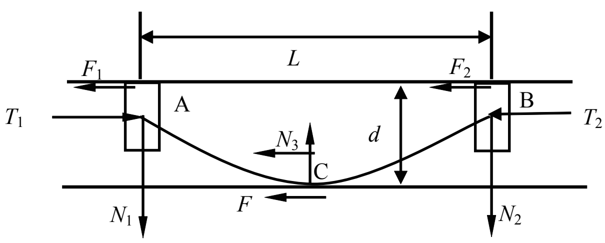

Figure 9
The Model for Calculating Friction of String with Packers in Horizontal Section

The mechanical analysis model of completion string with packers in horizontal section is shown in Figure 9. According to the friction law, establish mechanical equilibrium equation in horizontal and vertical direction.

$$\begin{cases} N_1 + N_2 = N_3 \\ T_1 = T_2 + \mu N_3 + \mu N_1 + \mu N_2 \end{cases} \tag{29}$$

Taking moments on C point of AC and BC section, according to moment equilibrium equation, the supporting force imposed on packer A from casing can be obtained by solving.

$$N_1 = \frac{(2d + L - 2\mu D_F - 2\mu d)(2d-1)D_F}{(L - 2\mu d)(2\mu d + L - 4\mu d D_F + 2\mu D_F)} T \tag{30}$$

The supporting force imposed on packer B from casing can be expressed:

$$N_2 = \frac{(2d-1)D_F}{L - 2\mu d} T \tag{31}$$

The supporting force imposed on the contacting point C can be expressed:

$$N_3 = \frac{(2d + L - 2\mu D_F - 2\mu d)(2d-1)D_F}{(L - 2\mu d)(2\mu d + L - 4\mu d D_F + 2\mu D_F)} T + \frac{(2d-1)D_F}{L - 2\mu d} T \tag{32}$$

The friction of packer A, B and the contacting point C can be expressed:

$$F_i = \mu N_i \qquad i = 1, 2, 3 \tag{33}$$

3. CASE STUDY

In order to verify the accuracy and reliability of the model, the Hongping 9 well in a certain block in Jilin oilfield is used as an example to calculate the effect of borehole ovality on the bare hole completion string tripping in friction. The depth measurement is 3195 m; the length of vertical section is 2017.99 m; the length of blending section is 342.48 m; the horizontal section is 834.53 m; the depth of intermediate casing is 2184.99 m. The completion string consists of drill pipe from well head to hanger, and there are packers, sliding sleeves and other downhole equipments under the hanger. The designed length of completion string is 1012.51 m; the outside diameter of the casing is 114.3 mm; inside diameter is 99.57 mm; the number of bare hole packers are 12; the outside diameter of the packer is 146 mm; the number of sliding sleeves are 11; and its outside diameter is 143 mm. The completion string structure diagram is shown in Figure 10.

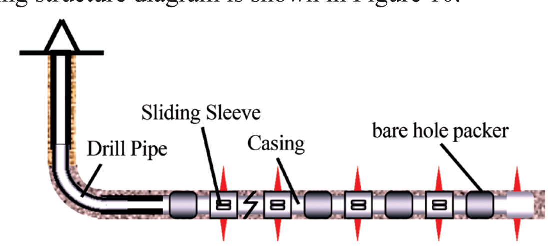

Figure 10
The Structure of Bare Hole Completion Packer String

The completion string is hung by the hook, when it is tripping into borehole. The value of hook load is the difference between the buoyant weight and friction of the string, and the value of hook load can reflect the friction of string. The distribution of hook load value calculated using the model considering the ovality and not considering ovality can be shown in Figure 11. The friction distribution of different ovality of the borehole is shown in Figure 12.

As can be seen from Figure 11, whether the measured or calculated hook load, the hook load are increasing linearly with the increasing of tripping in depth in the vertical section. The hook load decreases gradually, when the string trips into blending and horizontal section, because of the existence of friction. The declined value of hook load is great when the string just trips into the blending section. In order to decrease the probability of string tight pull, the distance between the packers of the frontal side string should be increasing. The hook load calculated using the model considering the ovality of borehole is in good agreement with the measured load. It can be concluded that the ovality impacts the string tripping in friction, and the model is accurate and reliable. As can be seen from Figure 12, the friction is small (almost zero) in vertical section, and in blending and horizontal section the friction is increasing gradually. With the increasing of ovality the friction is increasing. The ovality increases from 1.0 to 1.3, the increasing value of friction is 36.59 kN. The ovality of borehole has great impact on the tripping in friction. In order to decrease the ovality, the density of drilling fluid must increase.

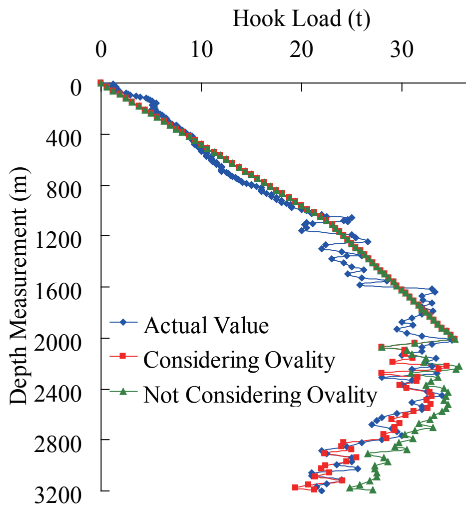

Figure 11
The Distribution of Hook Load Value Considering the Ovality and not Considering Ovality and the Actual Value

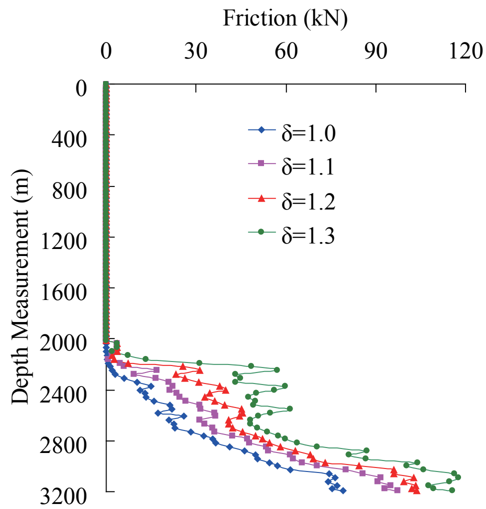

Figure 12
The Friction Distribution of Different Ovality of the Borehole

CONCLUSIONS

(1) Under the effect of non-uniform ground stress, the borehole becomes oval. The deformation regulations and friction calculation in oval borehole has great difference with which in circular borehole. In this paper, the string deformation model and the deformation model between two contacting points were established, and the determining method of the new contacting point of multi-packer completion string was proposed. The friction calculating model was established finally.

(2) The friction of completion string is almost zero in vertical section, and in blending and horizontal section the friction is increasing gradually. With the increasing of ovality the friction is increasing. The ovality increases from 1.0 to 1.3, the increasing value of friction is 36.59 kN.

(3) The ovality of borehole has great impact on the tripping in friction. In order to ensure the string tripping in smoothly, the density of drilling fluid must increase to decrease the ovality of borehole.

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