Research and Establishment of Drill String Safety Monitoring Model

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Abstract

In the horizontal well drilling process, the drill string works in a narrow hole filled with drilling fluid inside and outside, and usually bears pressure, bending, torsion, hydraulic pressure and other loads. The stress condition and downhole environment are abnormal and bad, resulting in frequent drill string safety accidents.The occurrence of such accidents will not only cause the abandonment of oil and gas wells, and even lead to casualties of construction personnel, seriously restricting the development of the oil industry.In the drilling process, drill string breakage, drill string fatigue damage, sticking and other drill string safety accidents are mostly caused by abnormal changes in friction torque and drill string stress, but at present the analysis of friction torque and drill string stress are still in static analysis, the real-time monitoring of friction torque and drill string stress are not mature.In view of this, this paper puts forward a kind of real-time monitoring of frictional torque and drill string stress by using surface instrument measurement data, which can ensure drill string safety. It is of great significance to select drill string reasonably, prevent drill string safety accidents and ensure drilling operation safety and reliability. Achievements: 1.By analyzing the adaptability of drill string safety monitoring, the parameters of drill string safety real-time monitoring are determined, and the technical scheme of drill string safety ground real-time monitoring system is designed. 2.The real-time monitoring model of frictional torque and drill string stress is established to provide theoretical and engineering basis for the development of real-time monitoring system for drill string safety, thus ensuring the safety and reliability of drill string construction.

Keywords

Drill string safety monitoring,Ground real time monitoring system,Friction torque,Drill string stress.

1. Introduction

Nowadays, horizontal wells will become the main means of increasing production and reserve in major oil and gas fields at home and abroad.But in the horizontal well drilling process, the drill string is working in a narrow hole filled with drilling fluid inside and outside, usually bearing pressure, bending, torsion, hydraulic pressure and other loads, and the stress state and downhole environment are abnormal bad.In the drilling process, the friction between drill string and borehole wall, bit and geological formation causes abnormal vibration of drill string, and the abnormal vibration of drill string will cause drill bit sticking and torque fluctuation, which will directly lead to drill string fracture or failure, and then lead to a series of derivative accidents.This greatly reduces the efficiency of drilling operations and increases the cost of drilling.With the continuous depletion of oil and gas resources, accurate and real-time monitoring of downhole drilling string safety is of great significance to reduce drilling costs and ensure safe and efficient drilling operations.

According to relevant research, drill string breakage, drill string fatigue failure, sticking and other drill string safety accidents are mostly caused by abnormal changes in friction torque, drill string stress.Therefore, the key technology of real-time monitoring of drill string safety is the real-time monitoring of friction torque and drill string stress.

At present, the bottom hole pressure torque can be monitored by downhole sensing in foreign countries, which provides a basis for judging drill string safety. But these equipment service costs are high, foreign has been industrialized promotion and application, domestic does not have the conditions, lack of practical value.At the same time, the drill string safety software developed abroad is mainly based on ground parameters to static analysis of friction torque and drill string stress, but these software are static analysis of a single data, can not achieve real-time monitoring of friction torque and drill string stress, and then realize real-time monitoring of drill string safety.Most of the monitoring systems developed independently in China monitor the abnormal changes of ground parameters in real time to judge drill string safety accidents artificially. They do not use ground parameters to monitor frictional torque and drill string stress in real time, so they can not guarantee drill string safety and reliability in drilling operation and realize real-time monitoring of drill string safety.Therefore, in view of the current monitoring situation at home and abroad, how to use surface measurement parameters to indirectly monitor drill string safety, and then broaden the application scope of surface instrumentation in the field of drilling engineering safety monitoring is of great significance.

Based on the investigation and analysis of a large number of literature on the mechanism and influencing factors of drill string safety monitoring, this paper analyzes the feasibility of real-time drill string safety monitoring using ground survey data, and optimizes the parameters of real-time drill string safety monitoring.At the same time, a real-time monitoring model for drill string safety is proposed by monitoring the friction torque and drill string stress.So as to ensure the safety of drill string on the ground real-time monitoring technology program, to provide a basis for the realization of drill string safety on the ground real-time monitoring.

2. Methodology

2.1 Study on safety monitoring mechanism of drill string

During drilling string operation, the abnormal changes of logging parameters such as hook load, torque, pump pressure and rotary speed can reflect the downhole situation. Although the abnormal changes of these parameters can reflect the downhole situation, if these parameters are monitored directly to determine whether drilling string safety accidents occur, it is extremely reliable and uncertain.

Firstly, these parameters do not necessarily change after drill string accidents occured, or even may change in the opposite direction. Secondly, there are many factors that cause these parameters to change, not necessarily due to drill string accidents.Therefore, it is necessary to study the method model to determine the direct parameters which can directly reflect the drill string safety, and these parameters can be obtained indirectly from ground survey data.

When drill string safety accident occurs, sticking will lead to the increase of friction torque; drill string fatigue damage will lead to the sudden change of drill string stress, the above parameters can be obtained indirectly through the establishment of the corresponding calculation model of ground survey data, the corresponding relationship as shown in Figure 1.

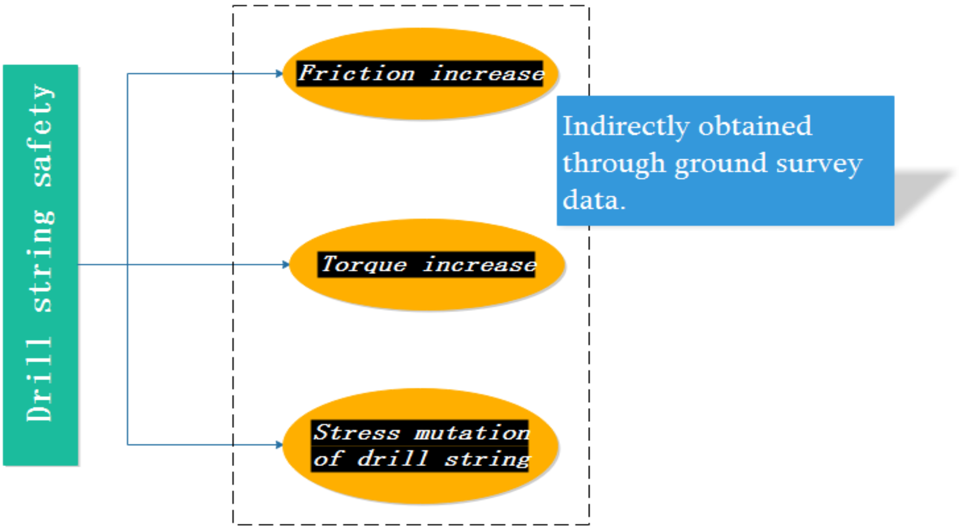


Fig.1 Parameter relation diagram of drill string safety monitoring

To sum up, friction torque and drill string stress are the most direct downhole monitoring parameters reflecting whether drill string safety accidents occur or not, and they can be obtained indirectly by only using surface measurement data.This meets the requirement of real-time monitoring of drill string safety through real-time monitoring of friction torque and drill string stress based on ground instrument measurement data.Therefore, friction torque and drill string stress are selected as monitoring parameters to realize the real-time monitoring of drill string safety and ensure the safe and efficient drilling operation.

2.2 Technical scheme design of real-time monitoring model for drill string safety ground

Based on the above analysis of drill string safety monitoring mechanism and influencing factors, through the feasibility analysis of drill string safety real-time monitoring using ground survey data, the technical scheme of drill string safety ground real-time monitoring model is designed.Model design is shown in Figure 2.

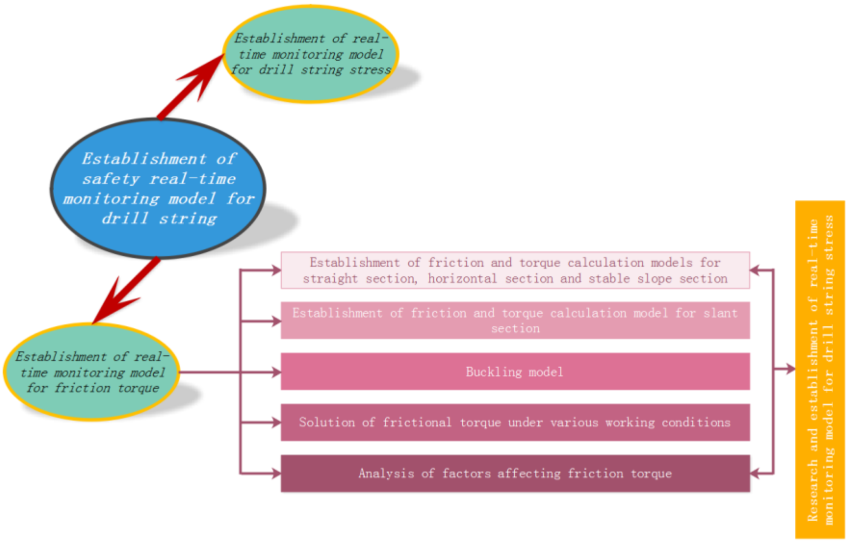


Fig. 2Model technical scheme design

Through the adaptability analysis of drill string safety monitoring engineering, the friction torque and drill string stress are determined as the direct monitoring parameters.Then, the real-time monitoring models of friction torque and drill string stress are established respectively, and the real-time and accurate dynamic monitoring of downhole parameters, friction torque and drill string stress is realized, so as to realize the real-time monitoring of drill string safety.

3. Analysis

In the process of drilling, different borehole trajectories directly lead to different contact modes between the string and the borehole wall. Therefore, different calculation models are needed to accurately calculate the friction and torque, so as to reduce the calculation error of friction and torque and improve the calculation accuracy of the friction and torque monitoring model.At present, the trajectory of horizontal wells is generally divided into three or five sections, namely, "vertical section +oblique section + horizontal section" or "vertical section + oblique section + stable section + oblique section + deviating section + horizontal section"[1]-[3].In this paper, five segment wellbore trajectory is used for analysis.

Because the borehole curvature of vertical section, horizontal section and stable deviation section is small, the string contacts with the borehole wall basically, but it may contain a certain curvature change and stiffness of drill collar, weighted drill pipe, so it is necessary to consider the effect of string rigidity on friction, so the modified soft model is adopted.

In the oblique section, because the hole curvature is relatively large, the pipe string can not be completely contacted with the wellbore after deformation, so the influence of the rigidity of the pipe string on the friction can not be ignored, so the three-dimensional longitudinal and transverse bending beam model is used to calculate.

3.1.1Establishment of friction and torque calculation models for straight section, horizontal section and stable slope section

The soft [4]-[5]model calculation is simple, and the accuracy of the model calculation is relatively high when the borehole curvature is very small or the stiffness of the string is very small, but the accuracy of the model calculation is very low when the borehole curvature changes greatly or the string stiffness is large.[6]

The hard model[2] is based on the soft model and takes into account the influence of the rigidity of drill string on the friction torque calculation model. When the curvature of borehole is large or the rigidity of pipe string is large, the precision of the model calculation is high, but the equation established by the model is very complex, so it is difficult to solve and the solution is difficult to converge. It is very sensitive to the data needed in the model, and the solution is very unstable.[7]

In view of this, the modified soft model is used in calculating the friction and torque of vertical, horizontal and inclined sections.

Assuming that the string is a flexible rope with only weight and no rigidity, and that the borehole center line is in continuous contact with the borehole wall, and ignoring the effect of shear force in the string, the force model of any element on the borehole trajectory curve is shown in Figure 3. According to force analysis, the formula for calculating axial force and frictional torque of unit section can be derived[1]-[11]:

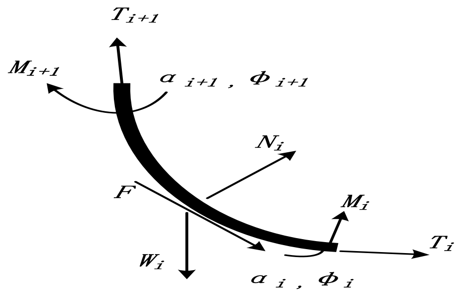


Fig. 3 Force model of microelement dl

$$T_{i+1} = T_i + (Wdlcos\alpha \pm \mu N_i) \tag{1}$$

$$M_{i+1} = M_i + \mu N_i r \tag{2}$$

$$N_i = \sqrt{(T_i \Delta\varphi sin\alpha)^2 + (T_i \Delta\alpha + Wdlsin\alpha)^2} \tag{3}$$

$$F = \pm\mu N_i \tag{4}$$

Where: T_{i+1} and T_i are the axial force of the upper and lower ends of drill string unit i, KN; M_{i+1} and M_i are the torque of the upper and lower ends of the drill string unit i, $KN\cdot m$; N_i is the direct contact pressure between drill string unit and shaft lining in section i, KN; W is the floating weight of unit drillstring, KN; μ is the coefficient of sliding friction,dimensionless unit; r is the radius of drill string unit, m ; F is a frictional resistance, KN; $\alpha, \Delta\alpha, \Delta\varphi$ are the average well inclination angle, the average well inclination angle increment and the azimuth increment respectively;When the drill string moves downward, take "-" ;when moving upward,take"+".

But when the curvature of local hole is large or the rigidity of drill string is large, the influence of rigidity of drill string on the whole calculation model should be considered. It is therefore necessary to add positive pressure to the well section. According to the constraint condition of shaft lining and the calculation method of beam deformation in material mechanics, the formula of additional rigid normal pressure N_g is obtained[12]-[15]:

$$N_g = 96EI[\frac{1-\cos\left(K\cdot\Delta L\right)}{K} - (D-D_0)]\Delta L^{-3} \tag{5}$$

$$\Delta L = \sqrt{[24(D-D_0)/K]} \tag{6}$$

Where: E is elastic modulus of drill string material, KN/m^2 ; I is the moment of inertia of drill string, m^4; K is wellbore curvature, $1/m$; ΔL is the length of drill string with additional rigid positive pressure on drillstring,m; D is borehole diameter, m; D_0 is the outside diameter of drill string, m .

3.1.2 Establishment of friction and torque calculation model for slant section

Both the soft model and the hard model are based on the assumption that the drill string and the borehole wall are completely in contact. However, the deviation section is not fully in contact with the borehole wall due to the large borehole curvature, so the soft model and the hard model are not applicable.Therefore, this paper adopts the method of establishing three-dimensional vertical and horizontal bending beam model [16]. That is, the connection point (hinge fulcrum) of the string is projected to the inclined plane and azimuth plane of the well, and then solved on these two planes separately. Finally, the solutions obtained on these two planes are combined to obtain the final results.

Assuming that the drill string in the inclined section has n + 1 hinge fulcrum, there will be n + 1 unknown number, then the pipe string in the inclined section can be regarded as composed of n-span pipe string, and then n-span pipe string can be established n-1 equation. At the same time, since the string at both ends of the deviation section is located in the horizontal section or the vertical section, the bending at both ends of the deviation section can be regarded as zero, thus two additional equations are obtained. So we can get n + 1 equation, and the number of unknowns is exactly n + 1. So we can get all the bending moments by solving the equations.According to the bending moments at each fulcrum, the supporting force at each pivot can be deduced. The formula is [2]:

$$N_i = \frac{M_{i-1} - M_i + T_{i-1}\left(y_i - y_{i-1}\right)}{L_i} + \frac{M_{i+1} - M_i + T_i\left(y_{i+1} - y_i\right)}{L_{i+1}} + \frac{q_i L_i + q_{i+1} L_{i+1}}{2} \tag{7}$$

Where: q_i is the unit length weight of the i cross drill string in drilling fluid, KN/m; M_i is the bending moment at the i fulcrum, KN/m; L_i is the length of the i cross drill string, m ; T_i is the axial stress of the i cross drill string, KN; y_i is the i bearing coordinate, m .

According to the formula (3-7), the branching forces N_{ip} and N_{iQ} at each fulcrum of the inclined and azimuth planes can be obtained respectively, and the total branching forces at the contact points can be obtained:

$$N_i = (N_{iP}^2 + N_{iQ}^2)^{1/2} \tag{8}$$

3.1.3 Buckling model

The buckling of drill string can be divided into sinusoidal buckling and helical buckling [18]-[19], as shown in Fig. 3-2.After the buckling deformation of the drill string, the shape of the drill string changes in the borehole, resulting in an increase in the force between the curved drill string and the borehole wall, which directly leads to the increase of friction and torque. The increase of frictional torque will further increase the buckling deformation of drill string, especially when the depth of well is large and the horizontal displacement is large.Table 1 is the critical load [20]-[23] for the drill string buckling obtained by foreign scholars:

Table 1 Critical load for buckling of drill string

Load	Shape
$\frac{F}{\sqrt{4EI\omega\sin\alpha / r}} < 1$	Non flexion
$1 < \frac{F}{\sqrt{4EI\omega\sin\alpha / r}} \le \sqrt{2}$	Sinusoidal buckling
$\sqrt{2} < \frac{F}{\sqrt{4EI\omega\sin\alpha / r}} \le 2\sqrt{2}$	Sinusoidal buckling or helical buckling
$2\sqrt{2} < \frac{F}{\sqrt{4EI\omega\sin\alpha / r}}$	Helical buckling

According to the experiment, when the axial force on the drill string exceeds the critical load when sinusoidal buckling occurs, sinusoidal buckling will occur. At this time, the positive contact pressure between the drill string and the borehole wall is added to the positive contact pressure generated by sinusoidal buckling deformation of the drill string in addition to the normal pressure obtained in the above model.That is:

$$\Delta \mathrm{N} = \frac{rT^2}{8EI} \tag{9}$$

When the axial force on the drill string exceeds the critical load when spiral buckling occurs, it will lead to spiral buckling of the drill string. In this case, the positive contact pressure between the drill string and the borehole wall is added to the positive contact pressure generated by the spiral buckling deformation of the drill string in addition to the positive pressure obtained in the above model.That is:

$$\Delta \mathrm{N}^{'} = \frac{r^{'}T^2}{4EI} \tag{10}$$

Where: $\Delta \mathrm{N}$ is the additional contact pressure;T is the axial force of drill string; r' is the 1/2 of diameter difference between borehole and drill string.。

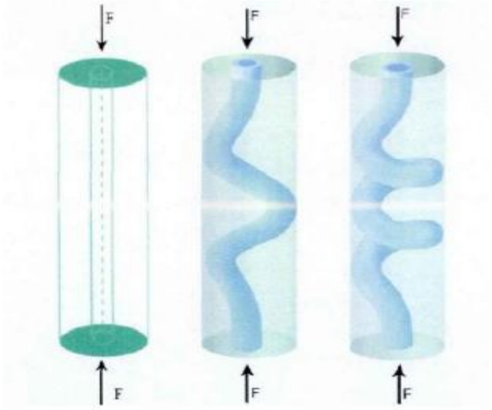


Fig. 4 Drill string balance (respectively, linear steady state, sinusoidal buckling state, helical buckling state).

3.1.4 Solution of frictional torque under various working conditions

1.Solution of frictional torque under drilling and sliding drilling conditions [2]-[4]

The axial force, buckling, contact force between drill string and borehole wall, friction resistance are coupled and influenced each other when drill string is in the condition of down-hole and sliding drilling.

In order to solve this model, it is assumed that the drill string is at rest in the borehole and the axial force is generated by gravity. Through the axial force, the critical load of buckling deformation can be analyzed. The contact force between drill string and shaft wall is solved, and frictional resistance (static friction) is solved.Then assume that the drill string slowly starts to move down the hole, ignoring the acceleration and dynamic effects produced by the drill string, and then by using static friction and axial force, a new axial force is obtained. Replace the new axial force with the first step.Repeat the above calculation until the difference between the new calculation results and the previous one is very small, and the cycle is ended, and the final friction torque is obtained.

2.Solution of frictional torque under drilling condition

When the drill string is in the start-up condition, the drill string has no rotation but only axial movement, at this time the drill string is only subject to friction resistance. When calculating frictional resistance under current working conditions, the drill string is in tensile state as a whole, so there is no need to consider the buckling of the drill string. Therefore, the method for calculating the frictional resistance at this time is the same as that described in the downhole and sliding drilling conditions, but the effect of buckling deformation is neglected.

3.Solution of frictional torque in rotary drilling and reverse drilling

When the drill string is in the condition of rotary drilling and reverse scratching, the drill string moves in both axial and rotary directions. The method and procedure for solving the drill string friction are the same as those described in the condition of down-hole and sliding drilling. The axial force of the drill string is obtained by the gravity and the pressure of the drill string itself, and the buckling state of the drill string is analyzed. The contact force between the drill string and the borehole wall is further calculated. Finally, the frictional torque of the rotary drilling and the reverse scratch hole is obtained.

3.1.5 Analysis of factors affecting friction torque

Friction is caused by the contact between drill string, casing and wellbore, so the main factors affecting friction are drilling parameters, string performance, wellbore conditions, lubricity and rock carrying capacity of drilling fluid, combination of drilling tools and drilling methods, hole cleanliness and other factors [24] - [25].

1.Effect of drilling parameters on friction resistance [19]

According to the experience of horizontal well construction, drilling parameters have a direct impact on drill string friction, of which drilling pressure and rotational speed have the most significant impact. For details, please refer to [19] below.

2.Effect of string performance on frictional resistance

(1) Influence of pipe stiffness

In horizontal wells, because of the hole bending, the greater the stiffness of the string, the greater the reaction of the wellbore, which leads to the increase of friction.

(2) Influence of string length

The influence of pipe length on friction is mainly from postive pressure and contact area. In horizontal wells, with the increase of the length of string, the positive pressure increases, and the contact area between string and wellbore will gradually increase, which leads to the increase of frictional resistance.

3.Influence of borehole condition on friction

(1)Influence of borehole curvature

In the design of horizontal wells, the curvature of borehole is larger than that of borehole, so it is difficult for drill string to rise and fall.

(2)Influence of shaft roughness

Generally speaking, the better the wall smoothness, the lower the friction coefficient, the smaller the friction and torque on the drill string.

4.Effect of drilling fluid on friction resistance [26]

The effect of drilling fluid on friction is mainly due to two factors: drilling fluid performance and drilling fluid viscosity.

(1)Effect of drilling fluid performance

The density of drilling fluid, the quality of mud cake, the viscosity of drilling fluid and the dynamic shear force will affect the inner and outer pressure difference of drilling string, the quality of borehole wall, friction factors, suspended sediment carrying capacity and so on. Increasing the pressure difference between the inside and outside of the string makes the drill string close to the wellbore, resulting in an increase in the contact area between the drill string and the wellbore, which leads to an increase in frictional resistance; poor quality of the wellbore, wellbore instability is easy to cause engineering accidents such as sticking and formation collapse; poor suspended sediment carrying performance of drilling fluid directly affects the ability of the drilling fluid to carry cuttings. It leads to debris deposition, which makes drilling string difficult and drilling speed down.

(2)Influence of drilling fluid viscous force

In order to illustrate the effect of drilling fluid viscosity on friction during casing running, a horizontal well in Liaohe oilfield was selected as an example to calculate the friction under the two conditions of considering drilling fluid viscosity and not considering drilling fluid viscosity.

The calculation parameters are: borehole diameter 215.9mm, casing depth 2080m, casing inner diameter 339.7mm, casing depth 150m, casing section friction coefficient 0.25, open hole friction coefficient 0.35, drilling fluid density 1.2 g/cm^3, viscosity 48s, drilling fluid apparent viscosity 19 $MPa \cdot s$, dynamic shear force 4.78Pa.

The result is shown in Fig. 5.

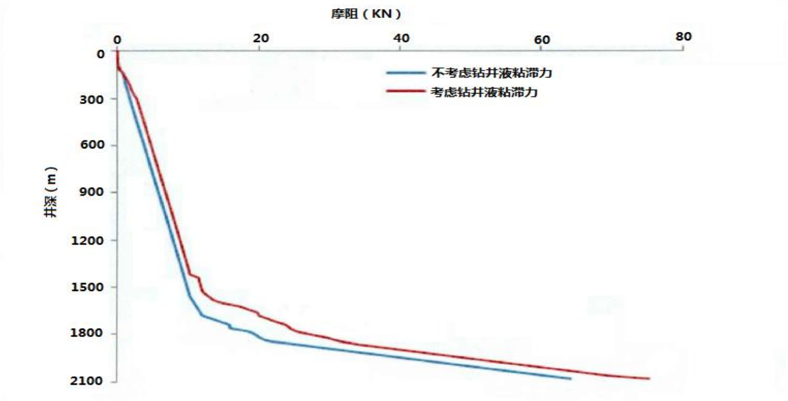


Fig. 5 Friction comparison of casing

From the above diagram, it can be seen that the friction is 64.30 kN when the well depth is 2 080 m and the friction is 74.85 kN when the viscous effect of drilling fluid is not considered. Therefore, it can be seen that the influence of the viscous force of drilling fluid on the friction is still relatively large.

4. Results

4.1 Drill string axial stress

The axial stress of drill string [27] is mainly produced under the condition of drilling pressure and self-weight. The formula for calculating the effective stress at any section of drill string is as follows:

$$\sigma_a = \frac{(L \cdot \gamma_s \cdot k_f - P)}{A} \tag{11}$$

$$k_f = 1 - \frac{D_0^{\ 2}\cdot(\gamma_0 + G_0) - D_i^{\ 2}\cdot(\gamma_i + G_i)}{(D_0^{\ 2} - D_i^{\ 2})\cdot\gamma_s} \tag{12}$$

$$G_i = \frac{p_b - p_a}{H} = \frac{0.2 f_i\cdot\rho_d\cdot H\cdot V_i^{\ 2}}{H\cdot D_i} = \frac{0.2 f_i\cdot\rho_{di}\cdot V_i^{\ 2}}{D_i} \tag{13}$$

$$G_0 = \frac{p_b - p_d}{H} = \frac{0.2 f_0\cdot\rho_d\cdot H\cdot V_0^{\ 2}}{H\cdot(D_w - D_0)} = \frac{0.2 f_0\cdot\rho_{d0}\cdot V_0^{\ 2}}{(D_w - D_0)} \tag{14}$$

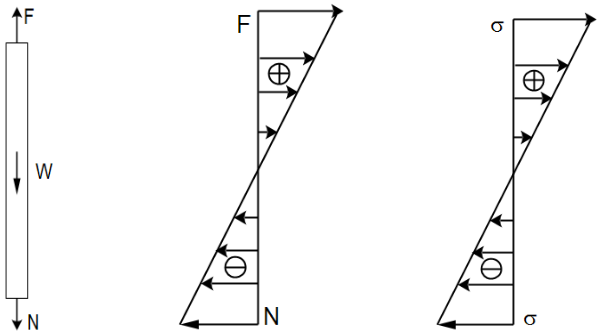
Internal friction coefficient of drill string:

$$f_i = \frac{0.0295\mu_{pv}}{\rho_{di} D_i V_i} \tag{15}$$

Annular friction coefficient:

$$f_0 = \frac{0.0295\mu_{pv}}{\rho_{d0}(D_w - D_0)V_0} \tag{16}$$

Where:L is the distance from the cross section to the bottom of the well,m; γ_s is a heavy material for drill string,N/ m^3; k_f is buoyancy coefficient; D_0 is the outside diameter of drill string,m; D_i is the bore diameter of drill string,m; D_w is the diameter of borehole,m; γ_i is the heavy drilling fluid in drill string,N/ m^3; γ_0 is the heavy drilling fluid outside drill string,N/ m^3; G_i is the pressure gradient of drilling fluid in drill string,N/ m^3; G_0 is the pressure gradient of drilling fluid outside drilling string,N/ m^3; ρ_{di} is the density of drilling fluid in drill string, kg/m^3; ρ_{d0} is the density of drilling fluid outside drilling string, kg/m^3; μ_{pv} is the plastic viscosity of drilling fluid, $Pa\cdot s$; V_i is the average velocity of drilling fluid in drill string,m/s; V_0 is the average velocity of drilling fluid outside drilling string,m/s;P is the drilling pressure,N;A is the cross-sectional area of drill string, m^2.



(a)Force analysis of drill string (b)Axial force (c)Axial stress

Fig.6 Axial force analysis of drill string

4.2 Drill string shear stress

When drilling normally, the torque is transmitted to the bit through the drill string, so there is shear stress on each cross-section of the drill string. Usually, the torque on the drill string depends on the power transferred to the drill string by the rotary table [28].

$$W = W_s + W_b \tag{17}$$

Where: W is the power transferred from the turntable to the drill string,kw; W_s is the power required when the drill string is idling,kw; W_b is the power required to drill and crush rock,kw.

The torque M of drill string is:

$$M = \frac{9549W}{n} \tag{18}$$

The drill string shear stress is:

$$\tau=\frac{M}{T_n}=\frac{9549W}{nT_n} \tag{19}$$

Where: n is the speed of drill string,r/min; T_n is the cross section torsional section coefficient of drill string, m^3.

$$T_n=\frac{\pi D_0{}^3}{16}(1-\frac{D_i{}^4}{D_0{}^4}) \tag{20}$$

In the case of normal drilling, factors affecting the power W include the type and diameter of the bit, rock properties, drilling pressure, rotational speed, mud properties and borehole quality. The empirical formula based on the test results can be calculated.

The required power W_s for drill string idling can be calculated by using the following formula (when the speed is n<230r/min):

$$W_s=4.6C\gamma_m D_0{}^2Ln \tag{21}$$

Where: γ_m is the thickness of mud,N/m; D_0 is the outside diameter of drill string,m;L is drill string length,m;C is a coefficient related to the inclination angle of a well.

Table 2. Correlation coefficient table between C and well inclination angle

Well slope angle	0°	6°	15°	48°
C	18.8×10^{-5}	31×10^{-5}	38.5×10^{-5}	48×10^{-5}

The power required for rock breaking by bits W_b:

(1)When drilling with a cone bit:

$$W_b=0.785PDn \tag{22}$$

(2)When drilling with a scraper bit:

$$W_b=0.3217P^{1.08}Dn\phi \tag{23}$$

Where:D is the diameter of the drill bit,m;nis the speed,r/min; ϕ is the empirical coefficient,it is related to rock property, mud property, cleanliness of well flushing fluid, wear degree of drill bit and other factors, generally taking 0.36~0.6.

The kinetic energy of drill string rotation is:

$$T=\frac{\omega^2}{2}J_0=\frac{\omega^2}{2}\frac{\gamma_s L}{g}J_p \tag{24}$$

Where:T is the kinetic energy generated when the drill string rotates; ω is the angular velocity of drill string; J_0 is moment of inertia; γ_s is the material of drill string; J_p is the polar inertia moment of drill string section.

The deformation potential energy U of drill string can be drawn from the following formula:

$$U=\frac{M^2L}{2GJ_p} \tag{25}$$

When stuck, kinetic energy is transformed into deformation potential energy instantaneously. Therefore:

$$T=U \tag{26}$$

That is:

$$\frac{M^2L}{2GJ_P}=\frac{\omega^2}{2}\frac{\gamma_s L}{g}J_p \tag{27}$$

Therefore, the maximum torque M_{max} is:

$$M_{max} = \omega J_p \sqrt{\frac{\gamma_s G}{g}} \times 10^3 \tag{28}$$

$$J_p = \frac{\pi}{32}(D_0{}^4 - D_i{}^4) \tag{29}$$

The maximum shear stress τ_{max} is:

$$\tau_{max} = \frac{M_{max}}{W_n} = \frac{M_{max} D_0}{2J_p} \times 10^6 \tag{30}$$

Where:M is the effective torque of drill string to drill bit;G is a rigid coefficient; τ_{max} is the maximum shear stress.

4.3 Bending stress of drill string

The magnitude of the bending stress is mainly determined by the reversal speed, and the effect of rotation on the bending stress is mainly to increase the bending frequency. Therefore, the bending stress of drill string is actually caused by the propagation of multi supported self excited transverse vibration along the drill string. The force and deformation of a single drill string subjected to longitudinal force under both rotation and reversal conditions are shown in Fig. 7 [29]-[30].

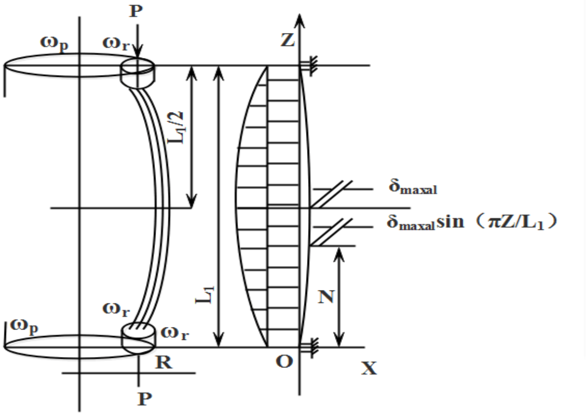


Fig. 7 Force and deformation of single drill string under rotation and inversion under longitudinal force

(1) When drilling, the positive and reverse angular velocities are:

$$\omega_p = \frac{D_0}{(D_w - D_0)} \omega_r = \beta \omega_r \tag{31}$$

$$n_p = \frac{D_0}{(D_w - D_0)} n_r = \beta n_r \tag{32}$$

$$\beta = \frac{D}{D_W - D} = \frac{D}{2R} \tag{33}$$

(2) Calculation of maximum bending stress of drill string

The influence of bending force on drill string can be divided into two parts: one is the effect of reversal of radius R, the other is the effect of self-excited lateral vibration of drill string. In formula 4-24, the drill pressure P is "+" when it is pulled, and is "-" when pressed, and the bending stress of the drill string is:

$$\sigma_w = \frac{\gamma_s \cdot A \cdot R \cdot \omega_p{}^2 \cdot L_1^2}{8g\text{（I/c）}} \left\{ 1 + 1.032 \frac{(\omega_P + \omega_r)^2 / \omega_{1al}{}^2}{\left| \left[1 - (\omega_P + \omega_r)^2 / \omega_{1al}{}^2 \right] \right| \pm (P L_1^2 / \pi^2 EI)} \right\} \tag{34}$$

$$\omega_{1al} = \frac{\omega_p + \omega_r}{\sqrt{1 \pm (PL_1{}^2 / \pi^2 EI)}} \tag{35}$$

$$\mathrm{I/c} = \frac{\pi \cdot \mathrm{D_0}^3 (1-\theta^4)}{32} \tag{36}$$

$$\theta = \frac{\mathrm{D_i}}{\mathrm{D_0}} \tag{37}$$

Where:R is the gyration radius of drill string,m; ω_p is the reverse frequency of drill string,rad/s; ω_r is the self rotation speed of drill string,rad/s; $\mathrm{L_1}$ is the length of single drill string,m;E is young's modulus of elasticity,Pa;I is the moment of inertia of drill string section, $\mathrm{m^4}$; $\mathrm{I/c}$ is the modulus of the drill string, $\mathrm{m^3}$.

4.4 Equivalent stress of drill string Von Mises

According to the above three principal stresses, the Von Mises equivalent stress σ_{mises} of the point can be obtained according to the fourth strength theory.:

$$\sigma_{\mathrm{mises}} = \sqrt{\frac{(\sigma_a - \tau)^2 + (\tau - \sigma_w)^2 + (\sigma_w - \sigma_a)^2}{2}} \tag{38}$$

Comprehensive stress intensity safety factor:

$$\mathrm{n} = \frac{\mathrm{Y_m}}{\sigma_{\mathrm{mises}}} \tag{39}$$

Where: σ_{mises} is a combined stress, kPa; $\mathrm{Y_m}$ is the minimum yield strength of drill string,kPa;n is a comprehensive stress intensity safety factor,dimensionless.

The drill pipe grade determines the minimum yield strength limit of the drill string, and different drill pipe grades correspond to different yield limits, as shown in Table 3.

Table 3. Table of minimum yield limit of drill pipe grade

Drill pipe grade	E	G	S	Z	V
Minimum yield limit (PSI)	75000	10500	13500	140000	150000

In order to ensure the safety of drill string section, it is necessary to ensure that the safety factor of comprehensive stress strength is greater than 1 in order to meet the strength requirements.

In the drilling process, the actual comprehensive stress strength safety factor is generally taken as the comprehensive stress strength safety factor n (>1.25).

If the coefficient does not meet the safety situation, the construction operation must be stopped, the drill string safety situation must be checked in an all-round way, and the drill string safety accident must be judged.

If it happens, measures such as replacing drill string should be taken to avoid serious drilling accidents, ensure drill string safety, and realize safe and rapid drilling operation.

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