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Structural Integrity of Casing Running in High-Angle Deviated Wells

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Abstract

High-angle deviated wells refer to drilling wells with complex wellbore trajectories and large dogleg severity. The complex trajectory and large dogleg severity can result in casing sticking, blockage, and even structural integrity failure during the casing running in the wellbore. A nonlinear large-deformation numerical method was established in this study to reveal the relationship between the structural integrity of the casing and wellbore parameters in high-angle deviated wells. A three-dimensional wellbore finite element model was built based on deflection data. The variations of friction, axial and radial contact stresses, and section deformation of the casing were investigated to evaluate the structural integrity of the casing based on the nonlinear contact analysis between the casing and the wellbore. Based on this investigation, the effects of wellbore curvature radius, casing thickness, and annular clearance on the structural integrity of the casing were discussed. Results demonstrate that, the friction of the casing increases in a fluctuating manner with the increase of running depth, reaching a maximum value of 1820.98 KN. In the deflecting section, the cross-sectional ellipticity of the casing is high, with a long-to-short axis ratio of 2.42. Thus, it is prone to local buckling failure. The larger the wellbore curvature radius and casing thickness are, the lower the frictional force and stress are during casing running. This finding indicates the good structural integrity of the casing. Increasing the annular clearance can reduce the additional loads induced by wellbore curvature, thereby decreasing the peak values of frictional force and stress. This study provides valuable references for the structural design and integrity evaluation of casings in high-angle deviated wells.

Keywords: High-angle deviated well, Casing, Bending deformation, Friction, Structural integrity

1. Introduction

High-angle deviated wells, the main means of remaining oil recovery, not only save operational costs but also improve recovery rate; thus, they are widely used in old oil production fields [1-3]. High-angle deviated wells are characterized by long wellbore sections, large dogleg severity, and significant depths. The casing undergoes deformation during the casing running in the wellbore because of the bending of the wellbore trajectory. Affected by the rigidity of casing structure, the bending deformation of the casing produces an additional bending moment, thereby increasing the axial tensile force and transverse shear force. In the well section with large dogleg severity, the additional loads imposed on the casing can cause local buckling or yielding, leading to structural integrity failure. Nonlinear mechanical problems, including dynamic contact and large casing deformation, complicate the evaluation of the structural integrity of casing running in high-angle deviated wells.

In the existing works, the nonlinear mechanical problems and structural integrity of casing running in high-angle deviated wells were studied [4-10]. However, scholars mainly employed static analysis methods to study the contact and large deformations of local casing segments without considering the dynamic contact and overall forces during casing running in high-angle deviated wells. The influences of wellbore angle changes and casing stiffness were overlooked. In addition, the influence mechanism of wellbore parameters (e.g., borehole curvature radius, clearance between casing and wellbores, and casing size) on casing strength/stiffness is unclear, thereby restricting the optimization design and integrity evaluation of casing structure. Therefore, the dynamic nonlinear contact between casing and wellbore in high-angle deviated wells must be analyzed, and the influence mechanism of wellbore parameters on casing strength and stiffness must be clarified to help improve the accuracy of evaluating the structural integrity of casings.

Given the limitations of experimental research and theoretical analysis, this study establishes a nonlinear large deformation numerical method to simulate dynamically the contact and deformation of the casing during casing running in high-angle deviated wells. This study aims to investigate the relationship between wellbore parameters and the structural integrity of the casing. The results can provide references for the structure optimization and integrity evaluation of casings in high-angle deviated wells.

2. State of the art

Scholars conducted considerable work on the contact stress, frictional force, and structural failure of casing during running in wellbore. In the aspect of static contact and frictional force study during casing running, Johancsik *et al.* [4] first studied the force condition of casing in the whole wellbore and proposed the "soft rope model" to analyze the

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frictional force of casing. However, the "soft rope model" applies only to the case of small casing stiffness or small curvature. It did not apply to high-angle deviated wells. Maida and Wojtanowicz [5] established the two-dimensional friction torque mechanical model and the three-dimensional friction torque mechanical model, which were further improvements and supplements of the Johancsik model. However, the models proposed by Maida still belong to the "soft rope model" because the influence of additional bending stress on friction torque was not considered. Regarding the dynamic contact and frictional force between the casing and wellbore, Zhu *et al*. [6] analyzed the dynamic contact force between the drilling tool and casing during sidetracking in high-angle deviated wells by using the piecewise rigidization method. However, the proposed dynamic contact model only aimed at the windowing process and did not further evaluate the structural integrity of the casing. Based on the sensitivity analysis and similarity principle of dynamic friction parameters in high-angle deviated wells, Zhu *et al*. [7] established a fast interpolation model of system parameters affecting friction. This model improved the calculation accuracy of dynamic friction. However, the model could not be directly employed to analyze the contact and friction between the casing and the borehole. Wen *et al.* [8] conducted experimental research on the contact wear of casing caused by vibration and studied the dynamic contact with casing. However, a dynamic contact test between the casing and the wellbore was not conducted.

In terms of the structural integrity and failure study of casings, Kiran *et al*. [9] analyzed the influences of casing thread fracture, casing corrosion, cement microannulus, and other factors on casing failure. However, the deformation during casing running in the wellbore was not considered. Noshi *et al*. [10] believed that the structural failure of casings was mainly caused by high circumferential stress without considering the prestress caused by the accessory load during casing running. Hamilton and Pattillo [11] analyzed the bending load induced by the rotary motion and the connection failure of casings. However, the bending load analyzed in the study differs from the additional bending load caused by well deviation, which was unsuitable for the failure analysis of the casing running in high-angle deviated wells. Wang *et al*. [12] studied the failure criterion of casing integrity in deep wells in Tarim Oilfield but did not analyze the influence mechanism of casing structure and wellbore parameters on casing failure. Lian *et al*. [13] conducted experimental research on casing wear in high-angle deviated wells and numerically analyzed the residual strength of the casing. However, the influence of the casing size and wellbore parameters was not discussed in the study. Khodami *et al*. [14] investigated the influence of casing spacing on casing integrity via sensitivity analysis and parameter tests by considering the environmental conditions of oil wells. However, the influence of the borehole curvature radius and casing annular clearance was not considered in the study. Mohammed *et al*. [15] discussed the casing failure mechanism caused by local load and induced stress in high-angle deviated wells. However, the study did not consider the additional stress induced by wellbore trajectory during casing running. This issue was crucial for high-angle deviated wells. Xie *et al*. [16] analyzed the deformation failure of casing structure caused by stress concentration and large deformation. However, the study did not consider the contact between the casing and the borehole. Yin *et al*. [17] discussed the stress yield and ovality deformation of the casing under fracturing extrusion. However, the effect of the wellbore curvature radius was ignored in the study. Ernens *et al*. [18] considered the effect of material parameters and welding on the connection failure of casing tools. However, the effect of casing size and wellbore annulus clearance were ignored. Yamada *et al*. [19] developed a small-scale casing structure stability model during reservoir compaction. The study focused on local casing failure without considering the influence of borehole curvature. Sathuvalli *et al*. [20] established a mechanical model of formation-cement sheath-casing system and quantitatively analyzed the influence of the formation load on the stability of the casing structure in the wellbore. However, further study on the influence of casing structure and wellbore parameters has not been conducted.

The above studies focused mainly on contact friction, wear, and casing failure during casing running in the wellbore, and the main method used was static analysis. Few studies considered the dynamic contact between the casing and the borehole in high-angle deviated wells (with large dogleg severity) and the influence of wellbore parameters on the structural integrity of casing. Hence, the present study proposes a nonlinear large-deformation numerical analysis method to analyze the dynamic contact of casing running in high-angle wells. The structural integrity of the casing and the effect of wellbore parameters are discussed using this approach.

The remainder of the study is organized as follows. Section 3 establishes the nonlinear large deformation numerical analysis method of casing running in high-angle deviated wells. Section 4 discusses the structural integrity of casing and the influence of wellbore parameters. Section 5 summarizes the conclusions.

3. Methodology

According to the data of oil and gas wells, a numerical model of casing running in the wellbore is established. The wellbore model of the curved section of the high-angle deviated well is composed of a vertical section, a horizontal section, and a curved section. In the finite element software ANSYS, the curved surface cannot be directly employed to establish the release pair because no contact model exists between curved surfaces. Thus, the straight segment is used in the finite element model to simulate the inner arc of the wellbore section. The entire arc-shaped contact surface of the wellbore comprises multiple curved surfaces with straight sections. The wellbore trajectory and the straight line of the inner arc surface are shown in Fig. 1. The dynamic contact numerical model of the casing in high-angle deviated wells is shown in Fig. 2. The inner diameter of the wellbore is 168 mm, the outer diameter of the casing is 131 mm, and the inner diameter of the casing is 110 mm.

The elastic modulus of the casing is 210 Gpa, the Poisson's ratio is 0.3, and the yield strength is 758 Mpa. The casing model is an elastic-plastic material, with elastic ultimate strength of 758 Mpa and the corresponding strain of 0.003609, and yield strength of 758 Mpa and the corresponding strain of 0.006. The borehole and casing are analyzed by SOLID 186 element, which has 20 nodes. Each node has x, y, z three degrees of freedom, and has many characteristics such as plasticity, stress hardening and large deformation.

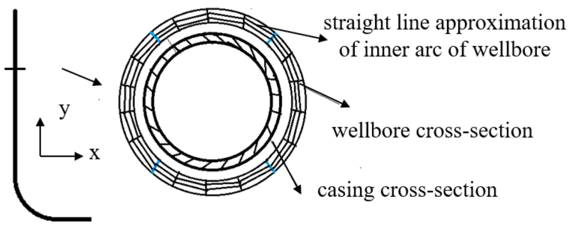

Fig. 1. Model of replacing arc with line for cross-section of high-angle deviated wells

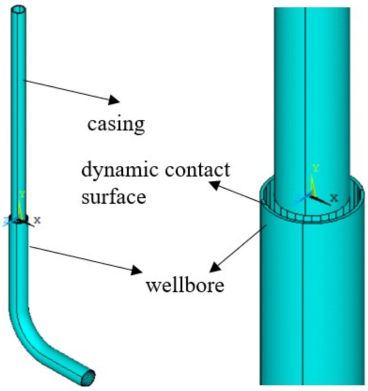

Fig. 2. Numerical model for dynamic contact of casing

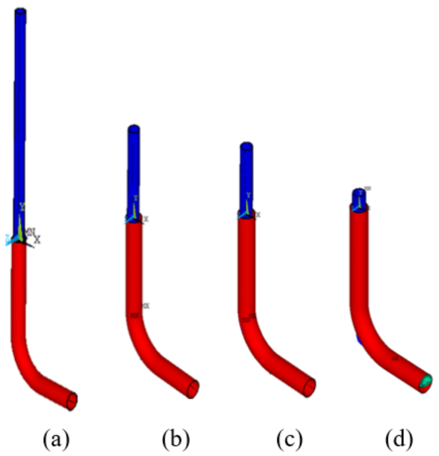

Fig. 3. Schematic diagram of casing running position at four time

The contact parts of contact model are casing and wellbore and contact pairs are set respectively. The contact between casing and wellbore is surface to surface contact. The outer surface of casing is set as the contact face, and the corresponding wellbore surface is set as the target face. The contact face units are CONTA174, and the target face units are TARGE170. Casing is subjected to downward pressure, contact stress and friction force of the wellbore. The shaft lining model is fixed with zero displacement constraint. At the same time, for the convenience of extracting the reaction force, the y-direction displacement of all nodes is coupled on the end face of the casing tail. The displacement constraint is added at the end of the casing, and the displacement of the upper end face of casing is the sum of the length through section and the total length of the wellbore. Surface pressure of 25 Mpa is applied on the upper end face of casing.

The dynamic process of casing running is simulated by ANSYS, and the schematic diagram of casing running position at four times (t = 5.41 s, t = 405.42 s, t = 705.42 s and t = 1000 s) are obtained as shown in Fig. 3.

4. Result Analysis and Discussion

4.1 Structural integrity evaluation of the casing during running

Figure 4 shows the variation of friction force during casing running in the high-angle deviated wells. The figure shows that the increase of running depth increases the resistance of the casing in a fluctuating manner. The resistance of the casing is the largest at the position with the maximum deviation, and the peak value is 1820.98 KN.

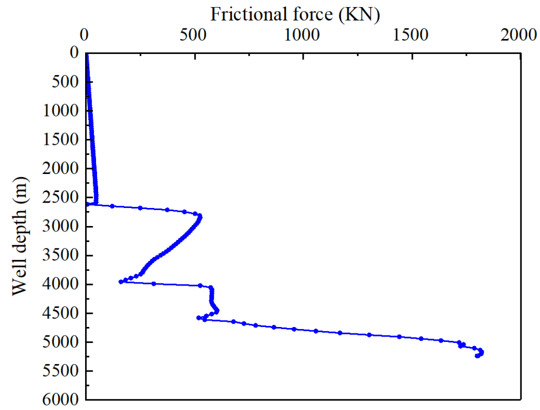

Fig. 4. The variation of frictional force with depth during casing running in high-angle deviated wells

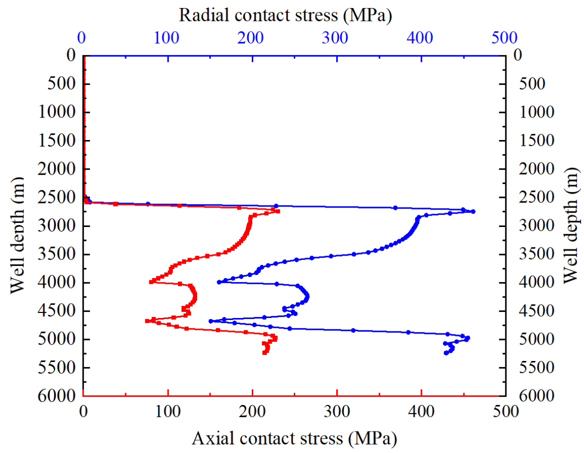

Fig. 5. Axial and radial contact stress variation during casing running in high-angle deviated wells

The variations of radial and axial contact stresses during casing running in high-angle deviated wells are shown in Fig. 5. It can be seen from the figure that with the increase of casing running depth, the maximum radial contact stress at the contact position first increases and then decreases. When the running depth is 2780 m, the radial contact stress of casing reaches peak value, which is 473.81 Mpa. With the casing running depth, the axial stress and radial stress of casing have a similar trend, and they are proportional. Similarly, when the depth is 2780 m, the axial contact stress of reaches the peak value of 235 Mpa.

Figure 6 shows the cross-sectional deformation of casing at the well depth of 2780m. The calculated long axis distance and short axis distance of casing after elliptical flattening deformation are 172.21 mm and 71.12mm respectively. The increase of long axis is 41.21 mm and the decrease of short axis is 59.88 mm. The ovalization degree of casing section in the deflecting section is the highest, and the ratio of long to short axis is 2.42.

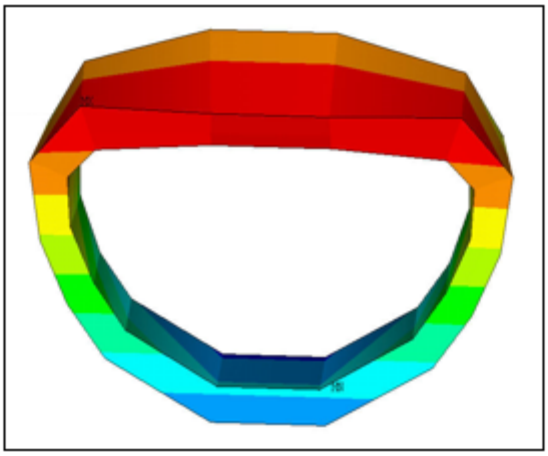

Fig. 6. Deformation of casing section

According to the data in Figs. 4 and Fig. 5, the von Mises stress during casing running in high-angle deviated wells is calculated to be 590.47 MPa. The yield strength of the casing is 758 MPa. Thus, the strength safety factor of the casing is 1.28, and the casing is in danger of local strength failure. According to the analysis data in Fig. 6, the maximum strain during casing running is calculated to be 0.32%, which is within the elastic range. This finding indicates that the casing deformation does not cause stiffness failure.

4.2 Factors affecting the structural integrity of the casing

To study the influence of borehole curvature radius on stress and deformation, the frictional force, Mises Stress and strain of casing are calculated under the three conditions of borehole curvature radius of 200 m (dog-leg severity is 8.6 °/30m), 300 m (dog-leg severity is 5.7 °/30 m) and 400 m (dog-leg severity is 4.3 °/30 m). The structural integrity of casing is evaluated. Fig. 7 shows the variation of casing friction force with well depth under different borehole curvature radius. The figure shows that the larger the radius, the smaller the value and fluctuation of the frictional force to casing running. Considering the reduction of resistance and degree of fluctuation, the large curvature radius can improve the trafficability. Fig. 8 shows the Mises Stress variation of casing under different borehole curvature radius. The smaller radius, the greater peak value of Mises Stress. The yield stress of casing is 758 MPa, so when the curvature radius is 200 m and 300 m, the casing has plastic deformation zone, and the well depth is 3700 m-4670 m.

The friction force, von Mises stress, and casing strain are calculated when the casing thicknesses are 11.5, 12.5, and 13.5 mm, respectively, to study the influence of the casing thickness on the contact stress. Moreover, the structural integrity of the casing is evaluated. Fig. 9 shows the frictional force variation with well depth for different casing thicknesses. The change in casing thickness slightly influences the casing frictional force. The increase of well depth results in a change of casing frictional force that is closely related to the change in dogleg severity. Fig. 10 shows the variation in the von Mises stress with different casing thicknesses. The smaller the casing thickness is, the greater the von Mises stress peak value is during casing running. When the thickness is 12.5 mm, the casing has a plastic deformation section with a length of 461 m. The thickness is 11.5 mm, the plastic deformation length of the casing increases to 628 m.

The stress and deformation of casing are calculated when the annular clearances between casing and wellbore is 14.5 mm, 18.5 mm and 20.5 mm respectively. Fig. 11 shows the frictional force of casing changing with well depth at different clearances. The increase of annular clearance will reduce the additional load of casing induced by wellbore curvature, thus reduce the frictional force of casing. When the annular clearance is increased by 1 mm, the casing frictional force drop will be reduced by about 140 KN. Fig. 12 shows Mises Stress variation of casing with well depth at different annular clearances. The increase of annular clearance will reduce the peak value of Mises Stress, but due to the influence of casing stiffness, the variation of Mises Stress with well depth is not obvious.

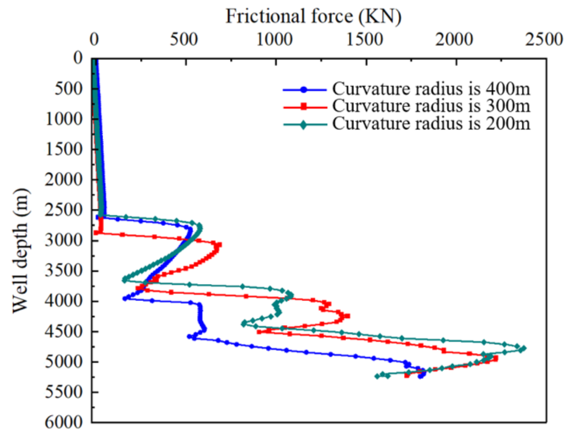

Fig. 7. Frictional force variation of casing with well depth under different curvature radius

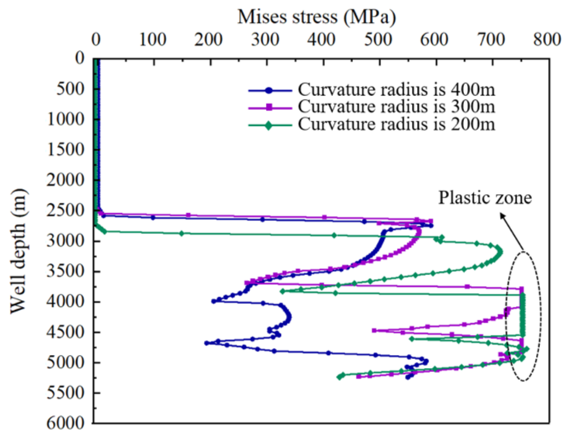

Fig. 8. Mises Stress variation of casing with well depth under different curvature radius

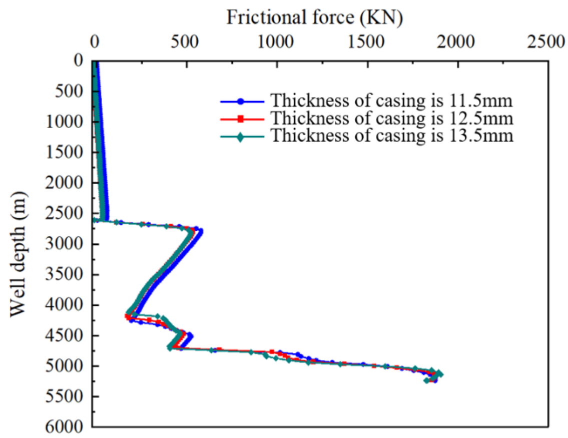

Fig. 9. Friction force variation of casing with well depth under different casing thickness

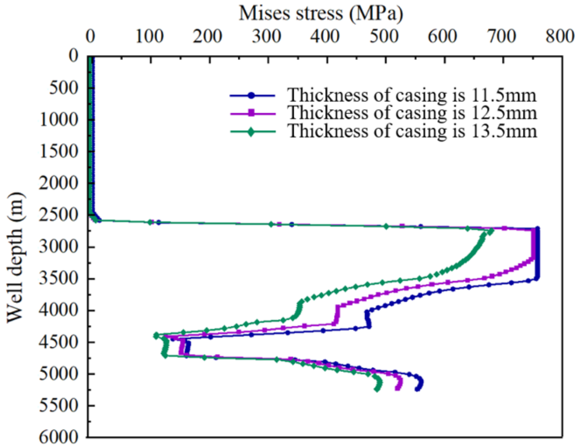

Fig. 10. The variation of Mises Stress of casing with well depth under different casing thickness

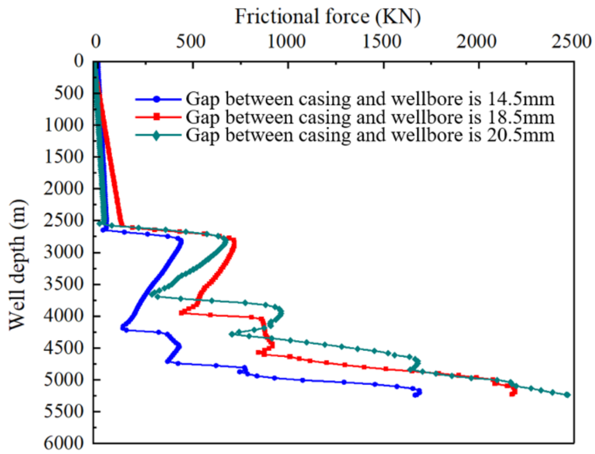

Fig. 11. The variation of frictional force with well depth at different annular clearance

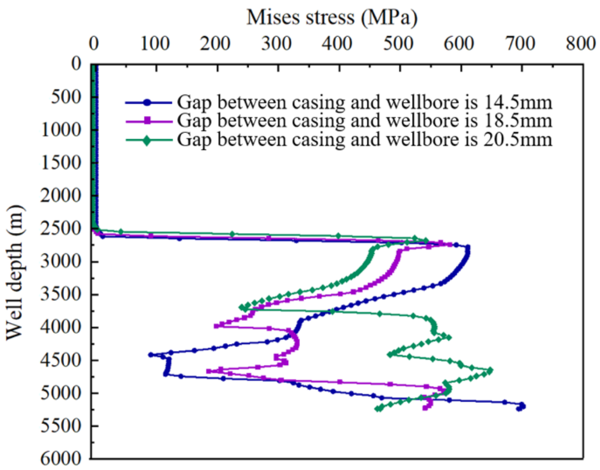

Fig. 12. Mises Stress variation with well depth at different annular clearance

Table 1 shows the cross-section deformation of the casing under different parameters (the dogleg severity is the largest at the well depth of 2780 m). The table shows that the variation of the casing ovalization degree under different parameter conditions is the same as that in the casing von Mises stress. The maximum strain value of the casing is 0.34%, which is less than the extreme value of casing stiffness failure of 0.36%. Thus, the casing does not buckle failure.

Table 1. Cross-section deformation of the casing during running under different parameters

Influencing factors		**Increased long-axis size**	**Reduced short-axis size**	**Strain**
borehole curvature radius	200 m	43.39 mm	61.89 mm	0.34%
	300 m	42.42 mm	60.29 mm	0.33%
	400 m	41.21 mm	59.88 mm	0.32%
casing thickness	11.5 mm	35.93 mm	35.06 mm	0.24%
	12.5 mm	32.15 mm	33.06 mm	0.22%
	13.5 mm	28.74 mm	33.02 mm	0.19%
clearance	14.5 mm	39.91 mm	69.09 mm	0.27%
	18.5 mm	39.42 mm	49.77 mm	0.26%
	20.5 mm	39.24 mm	47.61 mm	0.26%

5. Conclusions

A numerical simulation method was developed to study the structural integrity of the casing and its relationship with wellbore parameters in high-angle deviated wells. The dynamic parameters and strength (stiffness) failure of the casing were analyzed by the proposed method. The following conclusions can be drawn:

(1) Affected by the dogleg severity of well deviation, the frictional force of the casing increases in a fluctuating manner with the increase of running depth. The peak values of frictional force and stress appear at the position of maximum dogleg severity. At this position, the ovalization degree of the casing section deformation is also the highest, thereby increasing the tendency of strength and stiffness failure to occur.

(2) A large borehole curvature radius can reduce the frictional force and fluctuation amplitude of the casing running in high-angle deviated wells, and the trafficability can be improved. When the curvature radius is small, the casing produces plastic deformation.

(3) Increasing the clearance between the wellbore and casing reduces the additional load induced by wellbore curvature and reduces the casing friction. However, the variation of stress is not obvious because of the casing stiffness.

In this study, the nonlinear contact and large deformation problems of the casing in high-inclination wells are solved by numerical methods. A method for evaluating the structural integrity of casing is proposed. The proposed method has a certain reference value for casing structural optimization design. However, given the lack of test data in the current study, the method will be modified in future studies to improve the accuracy of structural integrity evaluation.

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