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Research on safety evaluation method for casing running in deep shale gas horizontal wells

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Abstract

To address the critical challenges of limited casing passing ability and premature casing deformation during casing running operations in deep shale gas wells in the Southern Sichuan Basin, this study develops a comprehensive mechanical model for casing running in curved wellbore trajectories. Analytical methods are introduced to determine the allowable annular clearance for free running, the maximum bend angle for forced running, as well as the casing strength and running resistance. A case study involving a deep shale gas horizontal well in Southern Sichuan was conducted, where numerical simulations were performed to validate key casing parameters. The results indicate that the proposed model effectively assesses the safety of the casing running process and provides a solid foundation for optimizing wellbore trajectory design. These findings offer valuable theoretical insights to improve casing running operations and enhance wellbore trajectory design, thereby contributing to increased operational safety.

Keywords

Safety evaluation; wellbore trajectory optimization; numerical simulation; annular clearance; bending stress.

1. Introduction

Horizontal wells are extensively utilized in shale gas exploration and development, where casing integrity is critical for the success of subsequent operations such as acidizing, hydraulic fracturing, production, and well workovers [1-3]. In deep shale gas wells, issues like limited casing flexibility and susceptibility to deformation during casing placement pose significant challenges that require immediate solutions. For instance, in a specific field within the Southwestern Sichuan Basin, 35 out of 61 wells experienced casing deformation, resulting in a deformation rate of 57.4%, with 27 of these wells deforming before fracturing. This presents a substantial challenge, particularly in developing the region's gas reservoirs, where complex and irregular wellbore trajectories in deep and ultra-deep horizontal wells lead to bending and deformation of the casing under gravitational forces. Such deformation compromises cementing quality and well integrity [4-6]. To address these challenges, multi-support casing combinations are commonly employed; however, they introduce high frictional resistance, complicating the placement of the casing at the designated depth while escalating development costs and safety risks. The issue of pre-fracturing casing deformation remains a critical safety concern during cementing operations, threatening subsequent stages such as acidizing and fracturing. Currently, no effective remedies exist for addressing casing deformation in deep shale gas wells. Therefore, it is imperative to establish a robust mechanical modeling approach for casing placement in deep shale gas wells and to elucidate the underlying mechanical mechanisms [9-12].

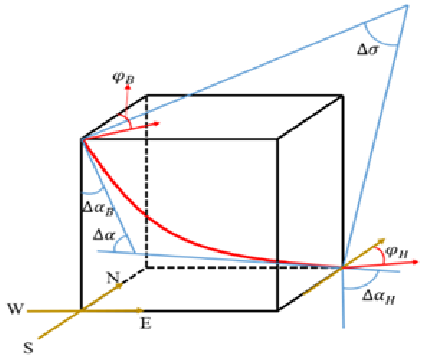
This paper addresses the safety concerns associated with casing placement operations in deep shale gas wells in the Southern Sichuan Basin. By integrating theoretical modeling, numerical analysis, and case validation, the study first establishes a mechanical model based on curved wellbore trajectories to analyze the mechanical behavior during casing placement. Subsequently, analytical methods are developed to determine the allowable annular clearance for free running, the maximum bend angle under forced placement, casing strength, and running resistance. Finally, by applying these methods to a deep shale gas horizontal well case, the safety of the casing placement is evaluated, confirming the model's applicability and providing robust theoretical and technical support for optimizing casing running operations and wellbore trajectory design.

2. Mechanical model

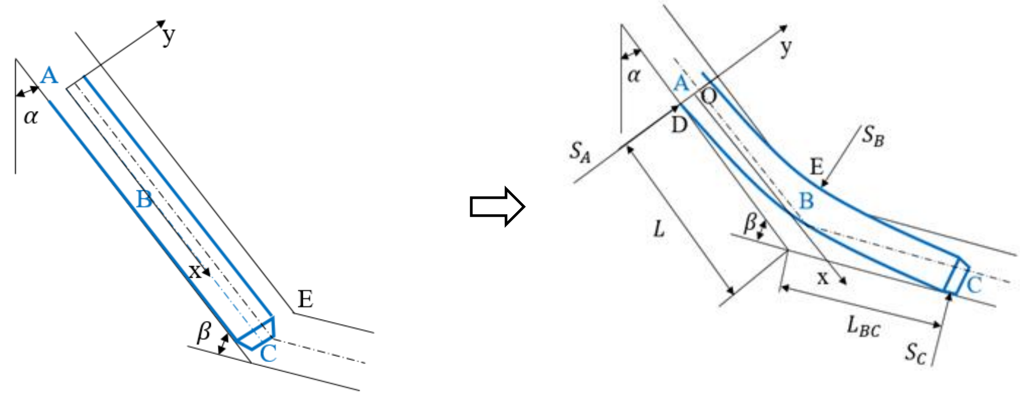
The mechanical model for casing placement in a curved wellbore is illustrated in Fig. 1. The wellbore section length is denoted by ΔL, with corresponding changes in inclination angle ($\Delta\alpha$) and azimuth angle ($\Delta\varphi$). When both the inclination and azimuth angles vary simultaneously, the total angular deviation of the wellbore axis along the length ΔL can be described using the Alexandrov equation:

$$\Delta\sigma = \sqrt{(\Delta\alpha)^2 + (\Delta\varphi \sin\alpha_{cp})^2} \tag{1}$$

in which, $\Delta\alpha = \alpha_B - \alpha_H$, $\Delta\varphi = \varphi_B - \varphi_H$ and $\alpha_{cp} = (\alpha_B + \alpha_H)/2$. $\Delta\alpha$ represents the change in inclination between the top and bottom of the wellbore section; $\Delta\varphi$ represents the azimuth change across the same section; α_{cp} is the average inclination angle along the wellbore section, with α_B and α_H representing the top and bottom inclination angles, respectively; φ_B and φ_H are the azimuth angles at the top and bottom of the wellbore section.



(a) Geometric model of full-angle variation in a curved wellbore



(b) Mechanical model of casing in a curved wellbore

Fig. 1 Mechanical model of casing running in wellbore

For the three-dimensional wellbore, the curvature radius of the wellbore axis is given by:

$$R = 57.3\frac{\Delta l}{\Delta \sigma} \tag{2}$$

Based on the beam-column theory, a mechanical model for casing placement in a curved section of the wellbore is established, as shown in Fig. 1(b). The differential equilibrium equation for the casing segment AB is expressed as:

$$EJy''(x) = S_A x - \int_0^x \left[P(y-\eta)\cos\alpha + P(x-\xi)\sin\alpha\right]d\xi \tag{3}$$

where S_A represents the reaction force exerted by the wellbore wall on the casing at point A (kN); α is the deflection angle of the casing at the microelement (rad); P is the distributed weight of the casing string (kN/m), and EI is the casing's flexural rigidity.

This mechanical model allows for the calculation of casing string deformation and stress distribution in response to complex wellbore geometries, ensuring that key parameters such as bending stress, contact forces, and insertion resistance are accurately quantified.

3. Analysis of Mechanical Parameters for Pipe-String Placement

3.1. Free fall annular clearance analysis

In the process of free-lowering a casing string into a deviated wellbore, it is assumed that the axial segment of the casing at the origin point O experiences no deflection. At point A, the outer diameter of the casing contacts the lower wellbore wall, while at point B, the casing is tangential to the upper wellbore wall without making contact. The boundary conditions for both extremities of the casing are formulated as follows:

$$y(0) = 0,\ \ y'(0) = 0 \tag{4}$$

$$y'(l) = \frac{1}{2}\beta,\ \ y'''(l) = 0 \tag{5}$$

where l is the projected distance between points A and B along the y-axis (m), and β is the bend angle of the wellbore axis (rad).

Employing the method of successive approximation and considering boundary condition (5), the equilibrium differential equation for the casing segment AB can be solved. The reactive force SA exerted by the wellbore wall on the outer diameter of the casing at point A is given by:

$$S_A = Pl\left(\sin\alpha + \frac{1}{2}\beta\cos\alpha\right) \tag{6}$$

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The y-axis projection of the AB segment length is expressed as:

$$l=\sqrt[3]{\frac{120\beta EJ}{80P\sin\alpha+53P\beta\cos\alpha}} \tag{7}$$

The minimum permissible annular clearance $\Delta_{\min}$ for free casing descent is formulated as:

$$\Delta_{\min}=\frac{420\sin\alpha+263\beta\cos\alpha}{28\left(80\sin\alpha+53\beta\cos\alpha\right)}\sqrt[3]{\frac{120\beta^4 EJ}{80P\sin\alpha+53P\beta\cos\alpha}} \tag{8}$$

3.2. Critical bending angle analysis for forced running

When the actual annular clearance is less than the minimum allowable clearance for free casing running, the casing must be forced through the deviated wellbore. The equilibrium differential equation for the casing segment AB remains consistent with Eq. (3). During forced descent, point A on the casing is constrained by contact with the lower wellbore wall, while point B contacts the upper wellbore wall. The boundary conditions are as follows:

$$y(0)=0, y'(0)=0 \tag{9}$$

$$y'(l)=\frac{1}{2}\beta, y(l)=\Delta \tag{10}$$

where Δ represents the annular space clearance between the wellbore wall and the casing.

By applying the method of successive approximations to solve the equilibrium differential equation for casing segment AB and incorporating boundary condition (10), we determine the reactive force exerted by the wellbore on the outer diameter of the casing at point A as follows:

$$S_A=\frac{\beta EJ}{l^2}+\frac{1}{3}Pl\sin\alpha+\left(\frac{2}{5}\Delta-\frac{1}{60}\beta l\right)P\cos\alpha \tag{11}$$

The y-axis projection of the AB segment length can be calculated by:

$$\frac{1}{12}Pl\sin\alpha+\left(\frac{\Delta}{7}+\frac{\beta l}{840}\right)P\cos\alpha-\frac{EJ}{l^2}\left(\frac{6\Delta}{l}-\beta\right)=0 \tag{12}$$

To ensure safe passage of the casing through a deviated wellbore, the bending stress must not exceed the yield strength of the material, as expressed in:

$$EJy''(l)\le M_H=\frac{\sigma_T}{K}W \tag{13}$$

in which, M_H represents the bending moment when the stress reaches the yield limit in the casing (MPa); σ_T is the yield limit of the pipe material (MPa); W is the section modulus of the casing (m^3); and K is the dimensionless safety factor.

Based on the condition for safe passage through the curved wellbore and the equilibrium differential equation for the AB segment, the allowable support force exerted by the wellbore on the outer wall of the casing at point A is calculated by

$$\left[S_A\right]=\frac{\sigma_T}{K}\frac{W}{l}+\frac{1}{2}Pl\sin\alpha+\left(\frac{3}{5}\Delta+\frac{1}{40}\beta l\right)P\cos\alpha \tag{14}$$

The critical allowable bending angle $\beta_{\max}$ is expressed as:

$$\beta_{\max}=140\frac{EJ\Delta}{Pl^4\cos\alpha}-\frac{70\sigma_T}{3K}\frac{W}{Pl^2\cos\alpha}-\frac{35\tan\alpha}{6}-\frac{8\Delta}{l} \tag{15}$$

At this point, the bending stress in the casing will reach its yield limit.

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3.3. Casing Hanger Resistance Analysis

When the casing reaches the wellbore deviation, point C on the casing is located at the inflection point of the trajectory, as illustrated in Fig. 1(b). The relative displacement of point C with respect to point B along the y-axis is:

$$y = \frac{1}{2}\beta l_{BC} - \Delta \tag{16}$$

where l_{BC} is the length from point B to point C along the wellbore trajectory (m).

The following relationship is derived from the displacement of point C relative to point B on the casing in the y-direction:

$$D = \frac{y_k}{y} = 2\frac{\beta l_{BC} - \Delta}{\beta l_{BC} - 2\Delta} \tag{17}$$

where y_k represents the vertical displacement of point C on the casing relative to point A (m).

Using the beam-column element theory and Eq. (17), the counteracting force exerted by the well wall on the casing outer wall at point C can be determined

$$S_C = 6\frac{EJy}{l_{BC}^3} = 6\frac{EJy_k}{Dl_{BC}^3} \tag{18}$$

During the process of running casing through a deviated wellbore, the displacement increment of the casing during deformation can be determined by:

$$\begin{cases} \delta_y = \dfrac{\beta}{D}\delta_{l_{BC}} \\ l_{BC} = l'_{BC} + \delta_{l_{BC}} \\ l'_{BC} = 2\dfrac{\Delta}{\beta} \end{cases} \tag{19}$$

where δ_{lBC} represents the displacement increment of the casing along the axial direction (m); δ_y represents the displacement increment of the casing along the y-direction when it undergoes axial deformation (m); and l'_{BC} represents the projection of the distance from point B of the casing to point C on the wellbore axis when the casing is not deformed axially (m).

When the casing is run along the wellbore trajectory, the counteracting force exerted by the wellbore wall on the casing outer diameter at point C is:

$$S_C = \frac{6EJ\left(\delta_y + y\right)}{\left(l'_{BC} + \delta_{l_{BC}}\right)^3} = \frac{6EJ\left(\beta\delta_{l_{BC}} + Dy\right)}{D\left(l'_{BC} + \delta_{l_{BC}}\right)^3} \tag{20}$$

The reaction force exerted by the wellbore wall on the casing outer diameter at point C can be used to calculate the bending moment at point B of the casing:

$$M_B = S_C\left(l'_{BC} + \delta_{l_{BC}}\right) = \frac{6EJ\left(\beta\delta_{l_{BC}} + Dy\right)}{D\left(l'_{BC} + \delta_{l_{BC}}\right)^2} \tag{21}$$

The equilibrium differential equation for the casing segment AB remains consistent with Eq. (3). During the casing running process, the outer diameter of the casing at point A is tangential to the lower wellbore wall, thereby constraining the y-direction displacement of the casing at point A. Simultaneously, the outer diameter of the casing at point B is in contact with and tangential to the upper wellbore wall, with the moment at point B determined by Eq. (21). The boundary conditions at both ends of the casing are as follows:

$$y(0) = 0,\ \ y'(0) = 0 \tag{22}$$

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$$y(l)=\Delta,\quad EJy''(l)=S_C\left(l'_{BC}+\delta_{l_{BC}}\right) \tag{23}$$

The counteracting force exerted by the wellbore wall on the casing outer diameter at point A is:

$$S_A=\frac{S_C}{l}\left(l'_{BC}+\delta_{l_{BC}}\right)\left(1+\frac{1}{120}\frac{Pl^3\cos\alpha}{EJ}\right)+\frac{7}{10}P\Delta\cos\alpha+\frac{1}{2}Pl\sin\alpha \tag{24}$$

$$S_A=\frac{6EJ\Delta}{l^3}+\frac{1}{4}Pl\sin\alpha+\frac{13}{70}P\Delta\cos\alpha-\frac{S_C}{168EJ}Pl^2\left(l'_{BC}+\delta_{l_{BC}}\right)\cos\alpha \tag{25}$$

Combining Equations (24) and (25), we obtain the counteracting force exerted by the wellbore wall on the casing outer diameter at point C:

$$S_C=\frac{EJ\left(\frac{420EJ\Delta}{l^2}-\frac{35Pl^2\sin\alpha}{2}-36Pl\Delta\cos\alpha\right)}{\left(70EJ+Pl^3\cos\alpha\right)\left(l'_{BC}+\delta_{l_{BC}}\right)} \tag{26}$$

The lateral support reaction SB of the wellbore wall at point B on the casing outer diameter can be approximated as the sum of the lateral support reactions SA and SC at points A and C, respectively:

$$S_B=S_A+S_C \tag{27}$$

The resistance that the casing experiences as it moves longitudinally through the wellbore is:

$$T=f\left(S_A+S_B+S_C\right) \tag{28}$$

where *f* represents the dimensionless resistance coefficient.

4. Case analysis

This section applies the aforementioned mechanical theories and methodologies to analyze the feasibility and safety of casing deployment in a shale gas horizontal well located in southwestern Sichuan. As illustrated in Fig. 2, the well employs a 'vertical-build-hold-drop-vertical-build-hold' double two-dimensional trajectory design. The inclination begins to increase at a depth of 300 meters to bypass obstacles and starts to decrease at a depth of 2280 meters. It increases again at a depth of 3420 meters to reach the target formation. The wellbore structure parameters are detailed in Table 1.Table 1 Wellbore structure data

Spud sequence	Well depth (m)	Bit size (mm)	Casing size (mm)	Casing wall thickness (mm)	Casing run interval (m)
First spud	80	660.4	508.0	11.13	0~78
Second spud	1070	406.4	339.7	12.19	0~1068
Third spud	2628	311.2	244.5	11.99	0~2626
Fourth spud	5851	215.9	139.7	12.70	0~5849

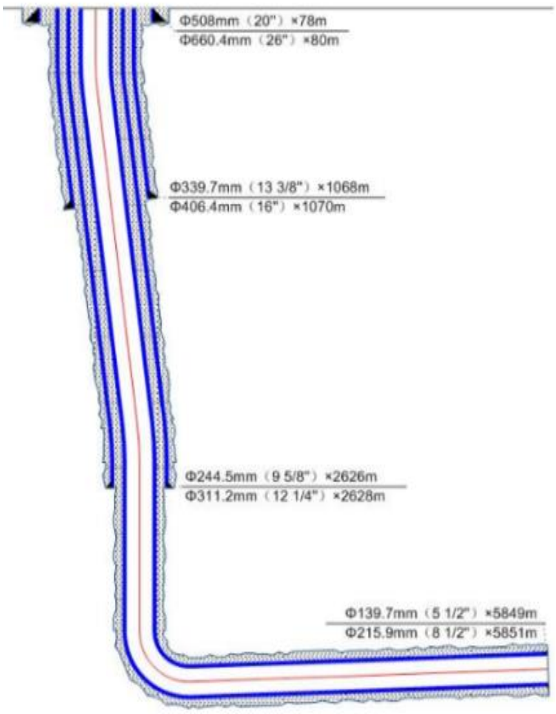
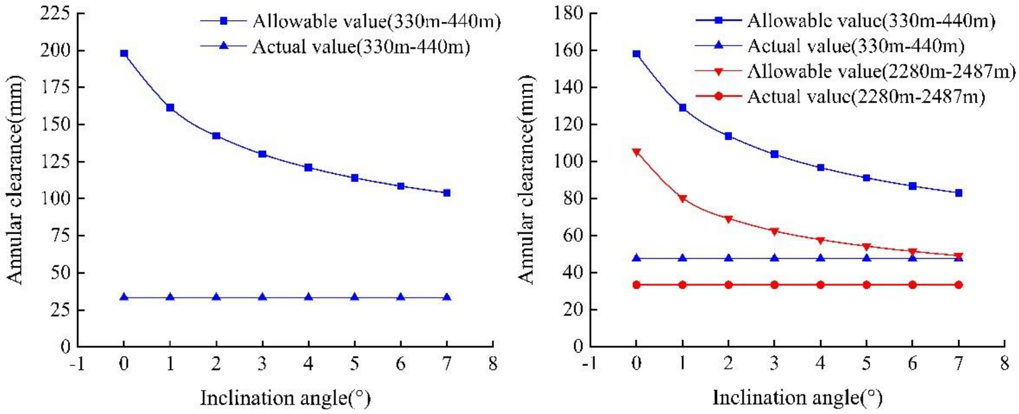


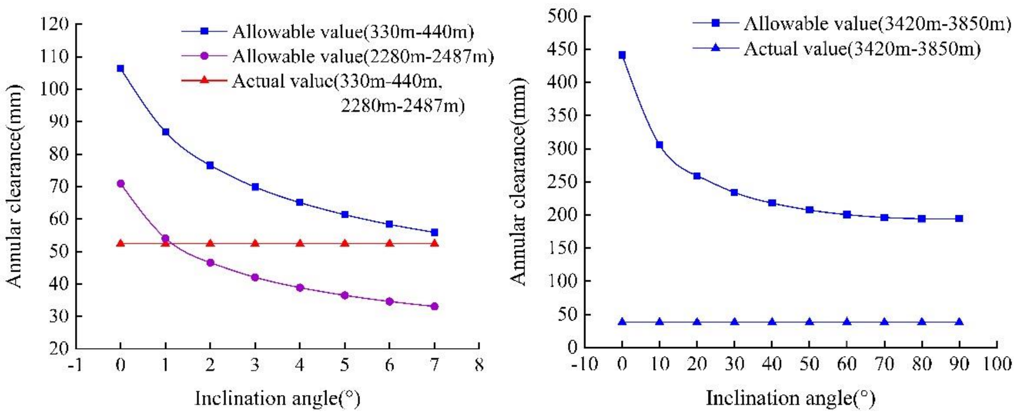
Fig. 2 Schematic diagram of wellbore architecture in a southwest Sichuan shale gas horizontal well

4.1. Analysis of free fall Annular Clearance

Fig. 3 illustrates the minimum allowable annular clearance for each casing string during free running when the casing is unconstrained. The analysis reveals that the surface casing, intermediate casing, and production casing all have a minimum allowable annular clearance exceeding the actual annular clearance at depths of 330-440 m, preventing free running through this curved wellbore section. The intermediate casing also cannot freely pass through the curved section at depths of 2280-2487 m. For the production casing at depths of 2280-2487 m, free running is impossible when the wellbore inclination angle is between 0 and 1°; however, it becomes feasible when the inclination angle is between 1° and 7°. Furthermore, the production casing cannot freely run through the curved section at depths of 3420-3850 meters.



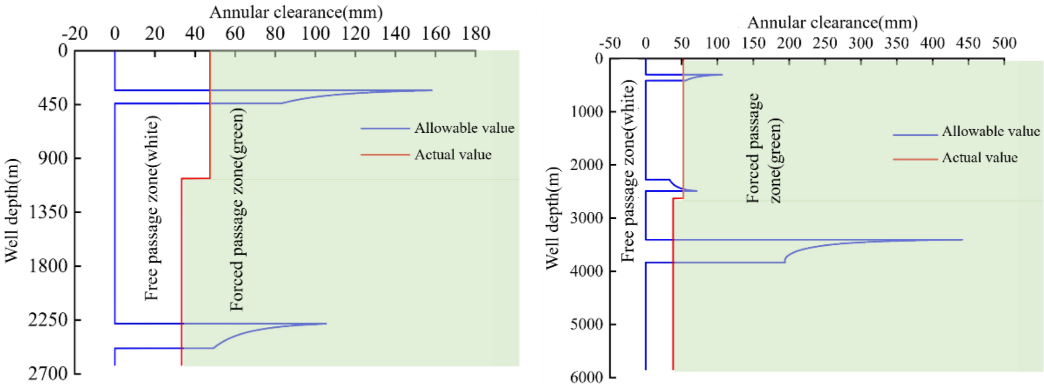
(a) Surface casing (b) Technical casing



(c) Oil layer casing (d) Oil layer casing

Fig. 3 Allowed annular clearance for free fall of casing

Fig. 4 illustrates the permeability of both the technical liner and the oil-bearing liner across the entire depth. At a depth of 330-440 meters, both liners experience a 30° increase in inclination, raising the angle from 0 to 7° as they navigate around an obstacle. The annular clearance between the outer casing's outer wall and the wellbore's inner wall is 33.35 mm, while the clearance between the technical liner's outer wall and the outer casing's inner wall is 47.6 mm, and the clearance between the oil-bearing liner's outer wall and the technical liner's inner wall is 52.4 mm, as shown in Fig. 4(a). From 2280m to 2487m, both liners decrease their inclination by 30°, returning the angle from 7° back to 0. The corresponding annular clearances are 33.35 mm between the technical liner and the wellbore wall and 52.4 mm between the oil-bearing liner and the technical liner, as seen in Fig. 4(b). At depths of 3420m to 3850m, the oil-bearing liner increases its inclination by 30° as it approaches the target, with the annular clearance between its outer wall and the wellbore wall reducing to 38.1 mm. As a result, the oil-bearing liner must be forced into the wellbore at this depth, as shown in Figure 4(b). Therefore, the oil-bearing liner needs to be forced into the wellbore at the depth of 3420-3850m.



(a) Technical casing (b) Oil layer casing

Fig. 4 Casing run-through for the entire well section

4.2. Analysis of casing forced running bending stress

For casings forced through curved sections, it is crucial to ensure that the bending stress does not exceed the material's yield strength to guarantee safe running. Based on the data in Table 1 and equations (12) and (13), the bending stresses for all casings when forced through curved sections were calculated, as shown in Fig. 5. The yield strength of the surface and intermediate casings is 773 MPa, with a maximum allowable dogleg severity of 6.5°/30m. When forced through the 330-440m build section, the bending stresses for surface and intermediate casings are 240 MPa and 120 MPa, respectively. The intermediate casing experiences 76 MPa when forced through the 2280-2487m section. These stresses are well below the material yield strength, ensuring safe running through curved wellbore sections. The production casing has a

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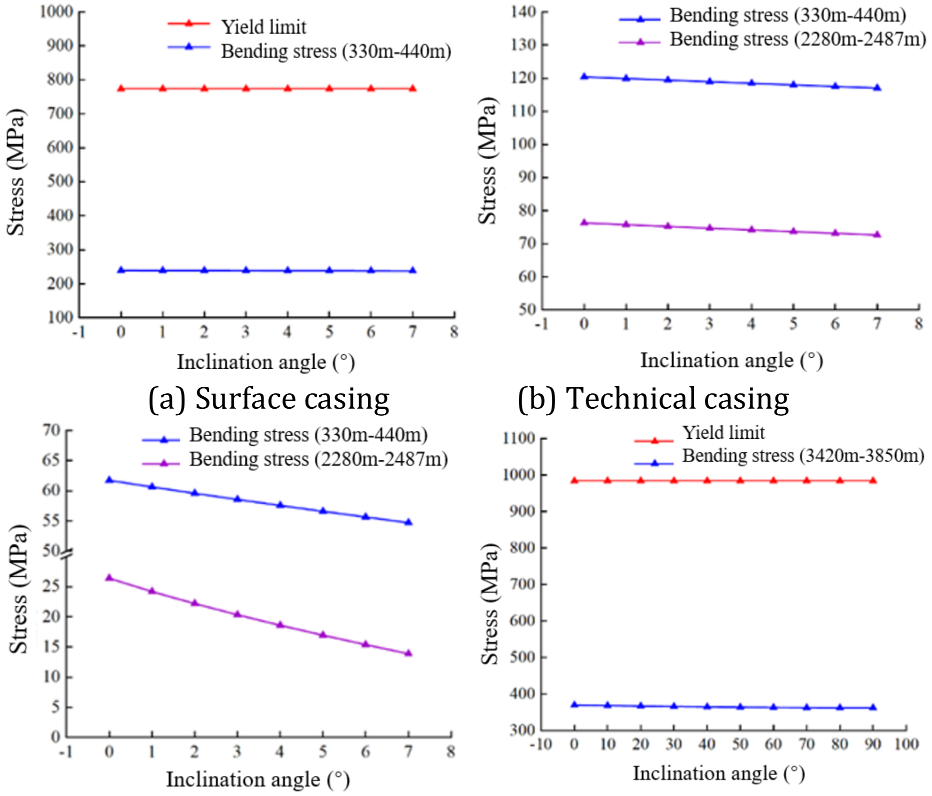
yield strength of 984 MPa and a maximum allowable dogleg severity of 7.2°/30m. When forced through the 330-440m, 2280-2487m, and 3420-3850m sections, the bending stresses are 62 MPa, 27 MPa, and 360 MPa, respectively. These values are also below the material yield strength, allowing for safe running.



(a) Surface casing (b) Technical casing

(c) Oil layer casing (d) Oil layer casing

Fig. 5 Casing bending stress

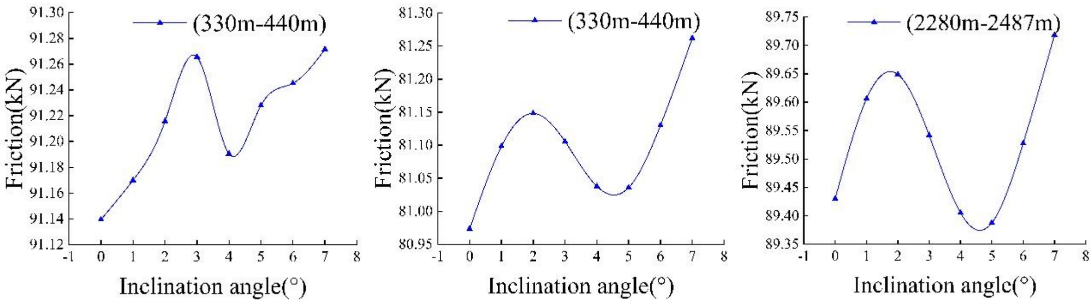
According to Eq. (15), the critical bending angles for each casing string were determined, as shown in Table 2. At a depth of 330-440m, the limit bending angle for the surface casing, which avoids plastic yielding in the well trajectory, is 2.69°. For the technical casing, the limit bending angles at depths of 330-440m and 2280-2487m are 3.79° and 3.17°, respectively. At a depth of 3420-3850m, the limit bending angle for the oil-bearing casing that prevents plastic yielding in the well trajectory is 5.06°. If the actual bending angle of the well trajectory remains below the theoretical limit for each casing level, the casings can be safely lowered. Conversely, if the actual bending angle exceeds this limit, the oil-bearing casing may experience unpressured deformation.

Table 2 Limit values of bending angles for various levels of casing

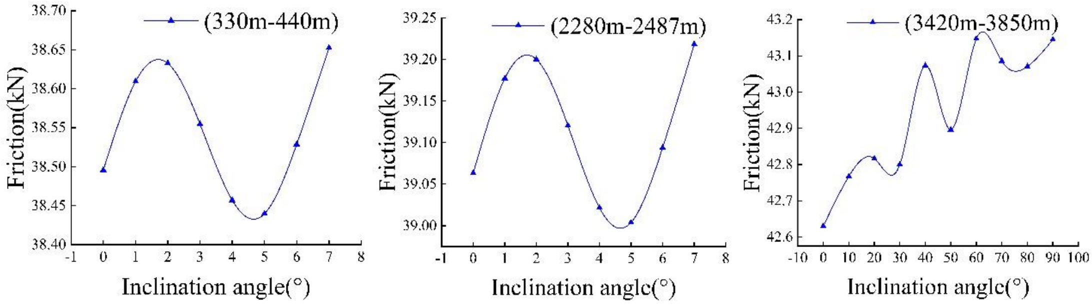
Casing Type	Drilling Depth (m)	Limit Bending Angle (°)	Actual Bending Angle (°)
Surface Casing	330-440	2.69	1.5
Technical Casing 1	330-440	3.79	1.5
Technical Casing 2	2280-2487	3.17	1
Oil-Bearing Casing	3420-3850	5.06	3.11

4.3. Analysis of Casing Hanger Resistance

To ensure smooth casing running to the target formation, the friction experienced during curved sections must be analyzed. Assuming a friction coefficient of 0.3, the casing running friction at each section was calculated using Eq. (25) to Eq. (28), as shown in Fig. 6. The casing lowering resistance exhibits an alternating trend of increases and decreases with the rising inclination angle of the wellbore. The maximum frictional resistance experienced by the surface casing, technical casing, and oil-bearing casing at depths of 330 to 440 meters are 91.27 kN, 81.27 kN, and 38.66 kN, respectively. At depths of 2280 to 2487 meters, the maximum frictional resistance for the technical casing and oil-bearing casing are 89.73 kN and 39.23 kN, respectively. Additionally, at depths of 3420 to 3850 meters, the maximum frictional resistance experienced by the oil-bearing casing is 43.18 kN. To ensure the casing can be lowered smoothly to the designated position, the axial force exerted on the casing must exceed the lowering resistance of the bending section.



(a) Surface casing (b) Technical casing (c) Technical casing



(d) Oil layer casing (e) Oil layer casing (f) Oil layer casing

Fig. 6 Casing running resistance

5. Conclusion

This study presents a comprehensive analysis of casing running operations in a shale gas horizontal well located in southwest Sichuan. The research encompasses the development of theoretical models and practical methodologies for evaluating casing free-running capabilities, bending stress during forced running, and frictional resistance during installation. By applying these models to a real-world case study, we have gained valuable insights into the mechanical behavior of casing strings in complex wellbore geometries and identified critical factors affecting the safety and efficiency of casing deployment. The findings of this study provide crucial guidance for optimizing casing design and installation procedures in challenging horizontal well environments. Based on our analysis, we draw the following conclusions:

(1) A methodology for calculating the allowable annular clearance for free-running casing was established. The analysis revealed that both the inclined obstacle section and the inclined target section necessitate forced running of the production casing.

(2) A computational model was developed to assess the bending stress on casing during forced running. The results indicate that the bending stress must not exceed the material's yield strength to prevent premature deformation of the production casing. The surface and intermediate casings have a yield strength of 773 MPa with a maximum allowable dogleg severity of 6.5°/30m, while the production casing has a yield strength of 984 MPa with a maximum allowable dogleg severity of 7.2°/30m.

(3) An analytical approach for evaluating casing running friction was proposed. The findings demonstrate that the frictional resistance fluctuates in correlation with changes in wellbore inclination. To ensure smooth casing deployment, the applied axial force must exceed the running friction encountered during installation.

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