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Calculating Method for the Axial Force of Washover String During Extracting Casing in Directional Well

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Abstract
In the process of extracting casing in directional well, the existence of inner casing and external centralizer makes the calculation of washover-string axial force more complex, which increases the difficulties for choosing a reasonable bit weight in construction with no doubt. In this paper, through taking three factors of casing contacting with washover tubing, centralizer and washover tubing contacting with well wall into consideration, an effective method for calculating the axial force conducting is established. Moreover, the axial force in different conditions is obtained through numerical solution. The calculation results are: (a) The casing has a less effect on the axial force conducting, and the axial force loss is mainly at centralizers and new contact points. (b) The axial force conducting can be improved effectively through setting a reasonable centralizer spacing. There is no doubt that the establishment of the method has an important significance for choosing the bit weight, judging whether the washover head cuts casing and designing washover string.

Key words: Axial force; Washover string; Extracting casing; Frictional resistance

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INTRODUCTION
Comparing with the process of extracting casing in straight well, the washover string for directional well uses centralizers with ball bearings or shaft sleeves. The existence of centralizer increases the outer diameter of the whole washover string, and makes the contact area of string and well wall larger; on the other hand, string between two centralizers will get deflection and buckling more easily, and there will be more contact points between string and well wall. These factors can increase the friction resistance of washover string during directional well extracting, and cause a significant impact on effective bit weight conducting[1-3].

Through our analysis, during extracting casing in directional well, the factors which affect the axial force conducting are: (a) The friction resistance caused by the contact of free casing strings which is with deflection or buckling and washover tubing after cement sheath is washed over. (b) The friction resistance generated by the contact of centralizers and well walls under the axial compressive stress. (c) The friction resistance which is induced by new contact point of washover strings between two centralizers with deflection or buckling and well wall under the axial compressive stress. By considering the factors which impact on axial force conducting during extracting casing in directional well, this paper establishes an effective method for calculating the axial force conducting. It can calculate the axial force of washover string with different centralizer spacing through segmental numerical solution. There is no doubt that the research results provide theoretical guidance for choosing reasonable bit weight during extracting casing in directional well.

1. FACTORS ANALYSIS ON AXIAL FORCE CONDUCTING

1.1 The Friction Resistance Between Casing and Washover Tubing

In the process of extracting casing, the gravity of casing string, the supporting reaction and the friction resistance of washover tubing inside wall, and pressure from inside and outside casing string are in combination. In natural coordinate system of wellbore, *t*, *n*, *b* present tangential, principal normal and binormal respectively. For force analysis, we take d*l* as casing string element, as it's shown in Figure 1.

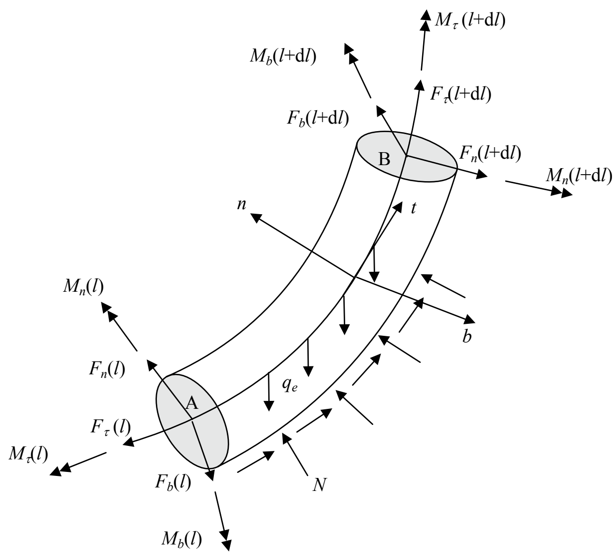

Figure 1
Mechanism Analysis of Casing Element

In the 3D curved borehole, considering stress balance of casing string on three directions, we establish deformation differential equations[4], as follows:

$$N = F_{e\tau} r \left(\frac{d\alpha}{dl}\right)^2 - EIr\left[\left(\frac{d\alpha}{dl}\right)^4 - 4\frac{d\alpha}{dl}\frac{d^3\alpha}{dl^3} - 3\left(\frac{d^2\alpha}{dl^2}\right)^2\right] + d_n\cos(\alpha-\theta) , \quad (1)$$

$$\frac{d^4\alpha}{dl^4} + \frac{d}{dl}\left[\frac{F_{e\tau}}{EI}\frac{d\alpha}{dl} - 2\left(\frac{d\alpha}{dl}\right)^3\right] + \frac{d_n}{EIr}\sin(\alpha-\theta) = 0. \quad (2)$$

Where,

$$\tan\theta = \frac{d_1}{d_2};\ d_1 = \frac{q_e \sin^2\beta}{k_0}\frac{d\gamma}{dl};\ d_2 = k_0 F_{e\tau} + \frac{q_e \sin\beta}{k_0}\frac{d\beta}{dl};$$

$$d_n = \sqrt{d_1^2 + d_2^2} = \sqrt{\left(\frac{q_e \sin^2\beta}{k_0}\frac{d\gamma}{dl}\right)^2 + \left(k_0 F_{e\tau} + \frac{q_e \sin\beta}{k_0}\frac{d\beta}{dl}\right)^2} .$$

Where, N is the contact pressure of casing string infinitesimal, N; $F_{e\tau}$ is the axial force of infinitesimal, N; E is the modulus of elasticity, Pa; q_e is buoyant weight of casing string in unit length, N/m; l is casing string length, m; r is difference of inner and outer washover tubing radius, m; α is the angle when axial line deviates from principal normal, °; β is deviation angle, °; γ is azimuth angle, °; k_0 is borehole curvature, 1/m.

On the basis of Equations (1) and (2), we can determine the casing situation inside the washover tubing during extracting, and calculate the friction resistance between washover tubing and casing string in different deformation states, thus estimating the effect of casing string on the axial force conducting for extracting casing.

1.2 The Friction Resistance at Centralizers and New Contact Points

1.2.1 Analysis of When Washover Tubing Between Two Centralizers Contacts Well Wall

In the 3D curved hole, axial force of washover tubing between two centralizers and centralizer spacing can bring different levels of deflection and buckling to washover tubing[5-7], and generate one or more contacts of washover tubing and top or bottom of well wall. The geometric relationship when washover tubing between two centralizers contact well wall, as it's shown in Figure 2.

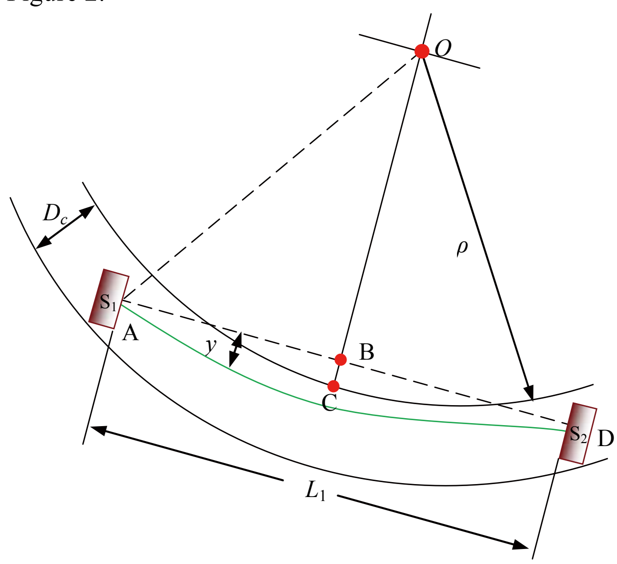

Figure 2
Judgment for the New Contact Point

On the basis of the geometric relationship in Figure 2, when washover tubing contacts top or bottom of well wall, the contact condition can be defined by:

$$y_{max} < \rho - \sqrt{\left(\rho + \frac{D_c}{2}\right)^2 - \left(\frac{L_1}{2}\right)^2} ,\ y_{max} > \rho - \sqrt{\left(\rho + \frac{D_c}{2}\right)^2 - \left(\frac{L_1}{2}\right)^2} + D_c . \quad (3)$$

Where,

$$y=\left(\frac{m_2}{k_2^{\,4}}-\frac{m_3}{k_2^{\,2}}\right)\cos(k_2x)-\left(\frac{m_1}{k_2^{\,3}}+\frac{\tan\theta_2}{k_2}\right)\sin(k_2x)+\frac{m_1}{k_2^{\,2}}x+\frac{m_2}{2k_2^{\,2}}x^2+\frac{m_3}{k_2^{\,2}}-\frac{m_2}{k_2^{\,4}},$$

$$k_1=\sqrt{\frac{P_2}{EI}}\;;\;k_2=\sqrt{\frac{P_1}{EI}}\;;\;m_1=\frac{N_1}{EI}\;;\;m_2=\frac{q_L}{EI}\;;$$

$$m_3=\frac{M_2}{EI}\;;\;\theta_2=\frac{k_1(L+L_1)}{2}.$$

Where, P_1 is the axial force of S_1, N; P_2 is the axial force of S_2, N; N_1 is the reaction force of well wall acting on S_1, N; q_L is weight of washover tubing per unit length, $q_L = q\sin\alpha$, N/m; M_2 is the inner bending moment of S_2, N·m ; I is the inertia moment of washover tubing, m^4; ρ is curvature radius at arbitrary point of washover tubing, m; D_c is wellbore diameter, m; L is the spacing between two centralizers, m; L_1 is the length of washover tubing between two centralizers, m; x is the distance between an arbitrary point and S_2 and we can have the maximum at y which is the midpoint of washover tubing.

1.2.2 Calculating Model of the Friction Resistance at Centralizers and New Contacting Points

By analyzing the stress of combination whose inclusions represents centralizer, washover tubing and centralizer respectively, as it's shown in Figure 3, and combining the static equilibrium equation of combination in x, y with the moment equilibrium equation of two centralizers[8], we can have the calculating model of the friction resistance from centralizers and contacting points.

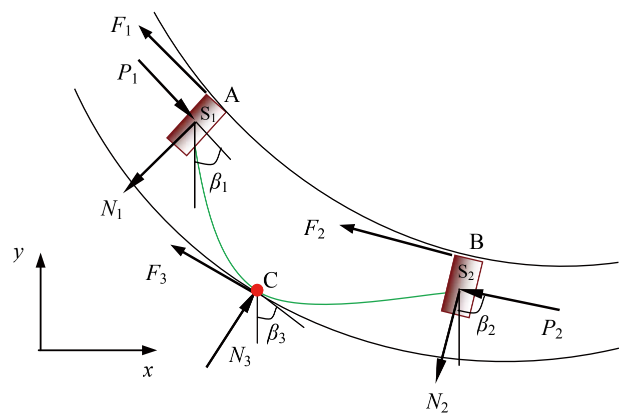

Figure 3
Friction Resistance at Centralizer and New Contact

The friction resistance of S_1 can be expressed as:

$$F_1=\mu\frac{(ab+1+\mu b)\cos\beta_2+(a+b)\sin\beta_2+b\sin\beta_2}{c(\cos\beta_1-a)+\mu(a\sin\beta_1-\cos\beta_1)-a\cos\beta_1}T_1\,. \quad (4)$$

The friction resistance of S_2 can be defined by:

$$F_2=\mu\frac{L\sin\beta_2}{L\cos\beta_2-\mu(L\sin\beta_2+D_F)}T_2\,. \quad (5)$$

The friction resistance of contact point is denoted:

$$F_3=\mu\frac{(a+b)\sin\beta_3+b(a+\sin\beta_2)}{\mu(a\cos\beta_3+b\cos\beta_1)}T_3\,. \quad (6)$$

Where,

$$a=\frac{\mu\sin\beta_3-\cos\beta_3}{\mu\cos\beta_3+\sin\beta_3}\;;\;b=\frac{L\sin\beta_2}{L\cos\beta_2-\mu(L\sin\beta_2+D_F)}\;;$$

$$c=\frac{L\sin\beta_1}{L\cos\beta_1-\mu(L\sin\beta_1+D_F)}\,.$$

Thus, as axial force of each contact point is known, on the basis of Equation (3), we can judge whether washover tubing between two centralizers contacts well wall or not. And the friction resistance of centralizers and contacting points can be calculated by Equations (4), (5) and (6). As a result, the effect of centralizer on the axial force conducting during extracting casing is estimated.

2. THE NUMERICAL METHOD FOR CALCULATING THE AXIAL FORCE

When we calculate the axial force of washover string during extracting casing in directional well, it refers to many high order differential equations, and will be different to derive the analytic solution. Therefore, the numerical method is necessary for the solution by dividing the whole casing string and washover tubing into m elements. During we calculate the friction resistance of casing string, by taking wellhead as boundary condition, the node partition is from top to bottom. For calculating the friction resistance of washover tubing, the boundary condition is downhole, and the node partition is from bottom to top. The process of numerical method for axial force calculating is shown in Figure 4.

3. CALCULATION EXAMPLE

In this paper, we take a casing damage well in Daqing as example. It is a directional well, and the casing damage point is at 300 m well depth. The well track is shown in Figure 5, and the required parameters are shown in Table 1. Using the numerical method, we calculate the axial force of washover string with different centralizer spacing without hook loading respectively, and the results are shown as Tables 2-4.

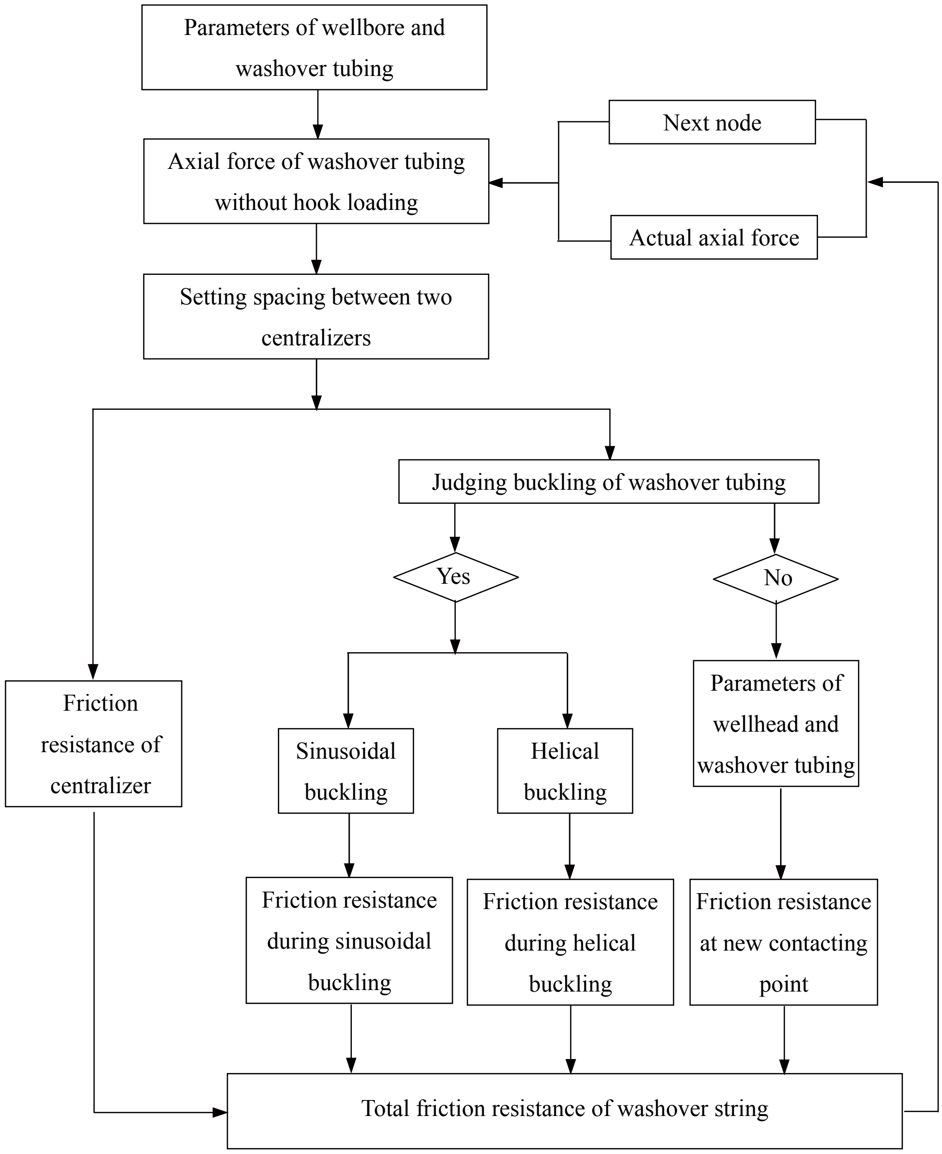

Figure 4
The Process of Calculating Axial Force

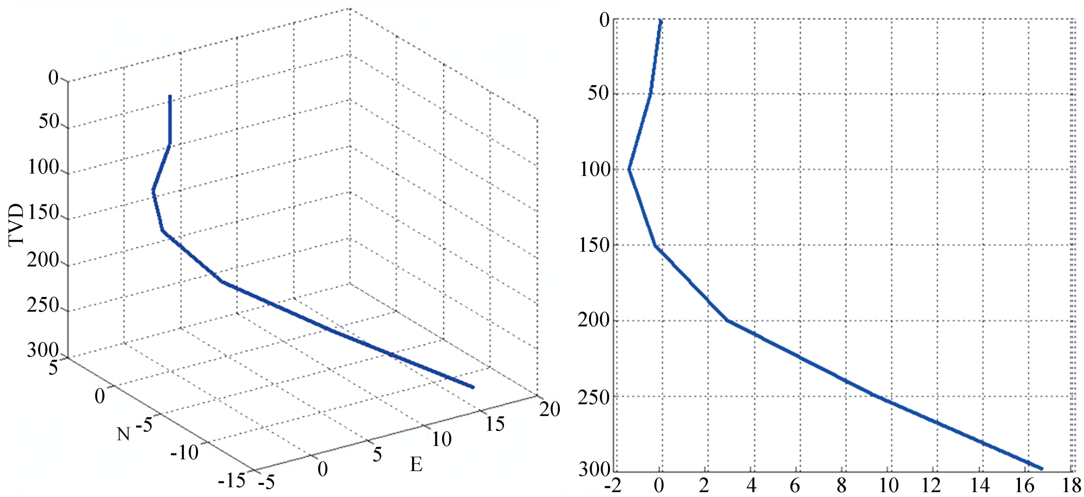

Figure 5
Well Trajectory of the Casing Damage Well

Table 1
The Parameters for Calculating

Parameters	Number
Casing string inner/outer diameter (m)	0.1271/0.1397
Washover tubing inner/outer diameter (m)	0.2266/0.2445
Casing string / washover tubing linear mass (kg/m)	20.83/53.57
Casing string / washover tubing elastic modulus (Pa)	2.06×1,011
Centralizer outer diameter /length (m)	0.265/1.014
Well depth of first centralizer (m)	150
Workover fluid density (kg/m^3)	1,690
Wellbore diameter (m)	0.33

Table 2
The Axial Force at 10 m Centralizer Spacing

Well depth (m)	Axial force without hook loading (kN)	Friction resistance at casing string (kN)	Friction resistance at centralizer (kN)	Maximum bending deflection between two centralizers (m)	Judging new contacting point	Friction resistance at contacting point (kN)	Actual axial force (kN)
150	73.65	0.853	0.65				73.65
160	78.63	1.079	1.27	0.4698	No	0	77.76
170	83.62	1.305	1.95	0.4715	No	0	81.25
180	88.60	1.531	2.67	0.4732	No	0	84.06
190	93.59	1.757	3.42	0.4751	No	0	86.15
200	98.57	1.983	4.18	0.4769	No	0	87.50
210	103.55	2.244	4.52	0.4785	No	0	88.04
220	108.54	2.506	4.84	0.5181	No	0	88.25
230	113.52	2.767	5.15	0.5318	No	0	88.13
240	118.51	3.028	5.44	0.5438	No	0	87.70
250	123.49	3.290	5.72	0.5684	No	0	86.98
260	128.47	3.656	5.69	0.5889	No	0	85.88
270	133.46	4.023	5.67	0.5917	No	0	84.81
280	138.44	4.390	5.64	0.6135	No	0	83.76
290	143.43	4.756	5.62	0.6486	No	0	82.73
300	148.41	5.123	5.60	0.7097	No	0	81.73

Table 3
The Axial Force at 20 m Centralizer Spacing

Well depth (m)	Axial force without hook loading (kN)	Friction resistance at casing string (kN)	Friction resistance at centralizer (kN)	Maximum bending deflection between two centralizers (m)	Judging new contacting point	Friction resistance at contacting point (kN)	Actual axial force (kN)
150	73.65	0.853	0.64				73.65
170	83.62	1.305	1.97	2.0723	No	0	82.51
190	93.59	1.757	3.56	2.8987	No	0	90.06
210	103.55	2.244	4.90	3.0269	No	0	95.99
230	113.52	2.767	5.85	3.5184	No	0	100.53
250	123.49	3.290	6.81	3.8189	No	0	104.13
270	133.46	4.023	7.09	3.9528	No	0	106.55
290	143.43	5.123	7.35	4.0199	No	0	108.70

Table 3
The Axial Force at 30 m Centralizer Spacing

Well depth (m)	Axial force without hook loading (kN)	Friction resistance at casing string (kN)	Friction resistance at centralizer (kN)	Maximum bending deflection between two centralizers (m)	Judging new contacting point	Friction resistance at contacting point (kN)	Actual axial force (kN)
150	73.65	0.853	0.64				73.65
180	88.60	1.531	2.75	1.9537	Yes	3.93	83.34
210	103.55	2.244	5.03	6.2094	Yes	6.76	88.07
240	118.51	3.028	6.65	9.0417	Yes	9.01	88.20
270	133.46	4.023	7.65	11.5971	Yes	10.48	92.88
300	148.41	5.123	8.26	12.6824	Yes	11.36	79.86

Through the analysis of data in Tables 2-4, we conclude that: (a) The key factors which have effects on axial force conducting of extracting casing are the friction resistance which are generated by casing string contacting with washover tubing inner wall, centralizer and new contacting point. Casing string has a less effect, and that means main axial force loss is caused by centralizer and new contacting point. (b) By reasonable design of spacing between two centralizers, the axial force during extracting can transfer effectively. To this casing damage well, its reasonable centralizer spacing is less than 25m, otherwise, washover tubing will contact well wall, and there will be a large friction resistance which has an effect of transferring on bit conducting.

CONCLUSION

(a) By considering deflection and buckling of casing string, as well as centralizer and washover tubing contacting with well wall, this paper establishes a model for calculating the axial force, and presents a new numerical method for solving it. As a result, it provides an important theoretical basis for proper selection of bit weight during extracting casing.

(b) For estimating whether casing string will be cut off after washover head contacts with casing, it's necessary to calculate the axial force during accurately. During extracting casing in different well sections, based on calculating results, selecting a reasonable bit weight can prevent casing string from being cut off, thus avoiding fish failing.

(c) As the axial force is known, the bending deflection of washover tubing between two centralizers can be calculated accurately. According to calculating results, we can calculate the proper centralizer spacing as the theoretical basis of the reasonable design of pipe strings for extracting casing in directional well.

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