Analysis of Intermediate Casing Wear in Ultra-deep Wells in China’s Tarim Oil Field

Chao Ma, Baokui Gao, Jieli Wang, Tianxiang Hu and Xingwang Chen

College of Petroleum Engineering, China University of Petroleum (Beijing), 18 Fuxue Road, Changping District, Beijing, China

E-mail: gaobaokui@126.com

Abstract. Intermediate casing wear with a spiral scar is often found in ultra-deep wells in Tarim Oil Field. In this work, the mechanism of such wear, and the measures to reduce wear are analyzed. Comparing the geometric characteristics of the wear scars, the root cause is found that the effective inner diameter of the casing is smaller than the outer diameter of the drill pipe joint after the uncemented casing helically buckled. To analyze the main factors affecting the helical buckling of the casing, the classical pipe mechanics theory is used and Well-X in Tarim area is taken as an example. The results show that too small hanging weight is the main cause of helical buckling of the casing. Besides downhole high temperature and large hole diameter enlargement rate are also important factors. The main measures, such as increasing the hanging weight, installing centralizers, and using graded cementation, have been proposed to reduce wear.

1. Introduction

Casing wear by tool joint is an increasing problem for drilling ultra-deep wells. This phenomenon can lead to a reduction on casing strength, lost production, and other hazardous problems [1]. Common casing wear usually results when the drill string tension forces the rotating tool joint into the casing on the concave side of a curved portion of the wellbore. Such casing wear often occurs in well sections with large deviation or large dogleg angle, and the resulting wear scars are usually straight. In Tarim Oil Field, however, intermediate casing wear with a spiral scar often occurs. The survey results show that the depth of ultra-deep wells in Tarim Oil Field generally exceeds 7000m and the intermediate casing is mostly more than 3500m. The main formations cemented by intermediate casing are Neogene, Paleogene, Cretaceous, Jurassic, Triassic, and Permian. The reverse cementation method is usually used for the intermediate casing. This method can be divided into three steps. First, the cement slurry is injected to the Triassic by the conventional cementation method. Then, the casing string is hung after the upper cement slurry is initially gelled. Finally, reverse cementing is performed.
to complete work. However, due to lost circulation during casing running or cementation, a large casing from surface casing shoe to Permian usually cannot be cemented and the length of free casing often exceeds 2000m. During the following drilling, the free casing will usually be worn with a spiral scar. Figure 1 shows the internal image of a casing section in Well-X in Tarim Oil Field. A clear spiral scar with a pitch of about 26m can be found in this picture. According to the preliminary analysis, such casing wear is directly related to the helical buckling of the free casing.

![Figure 1. The internal image of a casing section in Well-X.](image)

The stability analysis of pipe string has always been important for drilling engineering research. In 1950, Lubinski [2] analyzed the sinusoidal buckling behavior of string in the vertical wellbore. Later, Lubinski et al. [3-4] first proposed the concept of helical buckling of pipe string and derived the relationship between pitch and axial force in the vertical wellbore. The calculation model of the critical load of sinusoidal and helical buckling in different wellbore was obtained [5-7]. And then Mitchell [8-9] extended the helical buckling theory and solved the buckling problem by approximate analytical and numerical methods. In more recent years, many other scholars continued to study tubular stability, and great progress has been made [10].

The stability problem of pipe string has been studied in-depth, but there has been little research on the uncemented casing. Compared with the traditional study, the main differences of uncemented casing are as follows: (1) Both ends are fixed after cementation; (2) Its shape under each working condition is changed based on the previous one; (3) The degree of casing buckling is determined by changes in conditions such as downhole temperature, fluid density, and pressure; (4) The academic community has not reached a consensus on the calculation of the post-buckling of the pipe in the straight well.

In this work, the mechanism of casing wear with a spiral scar is analyzed by the geometric method. Then the main factors affecting the helical buckling of uncemented casing are studied by the classical pipe mechanics theory. Finally, some measures are proposed to reduce casing wear.

2. Casing wear analysis

In this section, causes of casing wear are first proposed. And then, taking Well-X as an example, the helical buckling of the uncemented casing and the main factors influencing the casing stability are analyzed using the classical pipe mechanics theory.

2.1. Causes of casing wear

This study found that the effective inner diameter of the casing will be greatly reduced after helical buckling, which is the main reason for casing wear. Figure 2 shows the effective inner diameter of casing in different states, where $D_{ah}$ is the effective inner diameter of the casing without buckling, $D_{ahb}$ is the effective inner diameter after helical buckling.

![Circumferential deployment angle (°)](image)

![Well depth (m)](image)
Figure 2(a) shows the casing string without buckling. In this case, the tool joint will not come into contact with the casing during drilling. Figure 2(b) is the casing string after the helical buckling. At this time, $D_{ah}$ is greatly smaller than the outer diameter of the tool joint, so that the drill pipe joints are forced away from the center of the borehole by the casing. Then a spiral mark will appear on the casing during drilling, like Figure 1.

2.2. Helical buckling of the uncemented casing

2.2.1. Assumption. The helical buckling analysis of the uncemented casing is based on the following assumptions: (1) The wellhead is taken as the origin of coordinates, and downward is positive; (2) The axially compressive force is positive; (3) Friction between the casing and the wellbore is neglected; (4) The transition section can be neglected and we focus only on the fully developed sinusoidal buckling and helical buckling section; (5) The curvature and the axial shortening caused by sinusoidal buckling will be neglected; (6) The hole enlargement rate is always the same.

2.2.2. Calculation model. Now there is no unified calculation model for the buckling of the uncemented casing, so some classical models are used in this study. The specific models are as follows:

1. The calculation formula of the equivalent axial force of the pipe can be expressed as [9]

   \[ F_a(x) = F_o(x) + P_i(x)A_i + P_o(x)A_o \]  \hspace{1cm} (1)

2. The load of critical sinusoidal buckling and critical helical buckling in straight hole are [7]

   \[ F_{cr} = 2.55\sqrt{EIq^2} \]  \hspace{1cm} (2)

   \[ F_{cr} = 5.55\sqrt{EIq^2} \]  \hspace{1cm} (3)

3. The axial shortening of the element caused by helical buckling will be [2]

   \[ d(\Delta x)_{hel} = \frac{F_{cr}r^2}{4EI} \]  \hspace{1cm} (4)

4. The change in unit axial length caused by thermal effect can be expressed as [2]

   \[ d_T = \alpha \Delta T \]  \hspace{1cm} (5)

5. The axial shortening of the element caused by pressure effect is [2]
The calculation formula of the pitch is [4]

$$d(\Delta \varepsilon)_s = \frac{2\mu \Delta P}{E \left(\frac{R^2}{R_2} - 1\right)}$$

(6) The expression of the curvature is [4]

$$\rho = 2\pi \sqrt{\frac{2EI}{F_e}}$$

(7) The expression of the curvature is [4]

$$C = \frac{4\pi^2 r}{p^2 + 4\pi^2 r^2}$$

(8)

In these equations, \(A\) is the cross-sectional area of the casing wall; \(A_i\) is the area corresponding to casing ID; \(A_o\) is the area corresponding to casing OD; \(E\) is Young’s modulus for tool; \(F_e\) is the actual axial force of the string; \(F_r\) is the equivalent axial force at the top of the element; \(I\) is the beam moment of inertia; \(P_i\) is the pressure inside the string; \(P_o\) is the pressure outside the string; \(q\) is the pipe weight per unit length; \(R\) is rate OD/ID of the casing; \(r\) is the clearance between casing and wall; \(\Delta T\) is average temperature variation in the wellbore; \(\alpha\) is coefficient of thermal expansion; \(\mu\) is the casing Poisson ratio.

2.2.3. Basic information about Well-X. The depth of Well-X is 8030m, and the average borehole diameter enlargement rate is 10%. The casing program of Well-X as shown in Figure 3.

![Figure 3. The casing program of Well-X.](image)

The reverse cementing method is used for the intermediate casing. But the casing from 1000m to 3780m cannot be cemented due to the lost circulation at the surface casing shoe and Permian. The fluid density and wellbore temperature at every stage are listed in Table 1, where Stage 1 to 4 represents the hanging weight, reverse cementation, formation fracture pressure test, and drilling respectively.

| Stage | Average fluid density in the casing (g/cm³) | Average fluid density between casing and well wall (g/cm³) | Variation of average temperature in the wellbore (°C) |
|-------|------------------------------------------|----------------------------------------------------------|--------------------------------------------------|
| 1     | 1.55                                     | 0                                                        | 1.24 Cemented                                    | 0                                                |
| 2     | 1.55                                     | 1.6                                                      | 1.24 Cemented                                    | 0                                                |
| 3     | 1.55                                     | Cemented                                                | 1.24 Cemented                                    | 0                                                |
In the first stage, the hanging weight is 120t. In the annulus, 0-1000m has no liquid, 1000-3780m is filled with the mixed working fluid. During the reverse cementation, a lost circulation occurred at the surface casing shoe. After this work, the annulus at 0-1000m is filled with cement slurry, and 1000-3780m is still filled with mixed slurry. The value of the formation fracture pressure test is 20MPa. During drilling, 127mm drill pipe with 165mm joint is used. At this stage, the free casing is severely worn. A spiral scar on the casing is presented in Figure 1.

2.2.4. Helical buckling of the uncemented casing at each stage. Figures 4 and 5 are the equivalent axial force and pitch distribution of the unsealed casing at each stage. It can be seen that the degree of casing deformation will be changed with the different working conditions, and the closer to the bottom of the well, the more serious the helical buckling of the casing.

![Figure 4](image.png) Equivalent axial force distribution at each stage.

![Figure 5](image.png) Pitch distribution at each stage.

After the casing string is hung, the helical buckling of the free casing is the most serious. At this stage, the length of the helical buckling casing is 2765.5m. During reverse cementing, the average density of the fluid in the annulus is increased by 34.7%. This leads to the total length of the casing with helical buckling is reduced by 17.29%. In the third stage, the internal pressure is increased which result in the helical buckling becoming severe. During drilling, the length of helical buckling casing is 2619.34m. According to calculation, the casing length with a curvature exceeding 4°/30m is 927m, which will undergo severe wear.

2.3. Analysis of influence factors
This part focuses on the main factors influencing the casing stability based on the data of Well-X.

2.3.1. Hanging weight. The equivalent axial force distribution of uncemented casing at different hanging weights as shown in Figure 6, where $T_w$ is the hanging weight. It is found that with the increase of the hanging weight, the helical buckling of the uncemented casing is greatly reduced. For instance, when $T_w$ is increased from 120t to 140t, the length of the helical buckling casing is reduced by 11.86%, and the minimum pitch increased by 6.13%. The results show that increasing the hanging weight can effectively reduce casing wear.

2.3.2. Wellbore temperature. Figure 7 is the equivalent axial force distribution of free casing at different wellbore temperature, where $\Delta T$ is the average temperature increment of the wellbore. The results show
that with the increase of the average temperature, the helical buckling of the free casing gradually becomes serious. With ΔT raise from 10 °C to 20 °C, for example, the axial force at the lower end of the free casing increased by 11.37%, and the minimum pitch decreased by 5.24%. Therefore, it is very important to accurately predict the formation temperature before construction.

![Figure 6. Equivalent axial force distribution at different hanging weights.](image)

![Figure 7. Equivalent axial force distribution at different wellbore temperatures.](image)

2.3.3. **Hole diameter enlargement rate.** The curvature distribution at different hole diameter enlargement rates is presented in Figure 8. The helical buckling is gradually aggravated with the increase of the diameter enlargement rate, and the closer to the bottom of the well, the greater the degree of increased buckling. Such as with the rate increased from 10% to 15%, the length of casing a curvature exceeding 4°/30m is increased by 27.83%, and the maximum bending stress of casing increased by 16.18%.

![Figure 8. The distribution of curvature at different hole diameter enlargement rates.](image)

![Figure 9. Schematic diagram of effective inner diameter after using some centralizers.](image)

3. **Measures to reduce wear**

Through the above analysis, the following suggestions are proposed to reduce casing wear:

1. Choosing the appropriate hanging weight. Increasing the hanging weight can effectively reduce the helical buckling of the free casing. However, too much hanging weight will affect cementing quality. So this parameter should be determined according to the construction situation.

2. Using some centralizers. This measure can increase the effective inner diameter of the casing after helical buckling. Figure 9 is the schematic diagram of the effective inner diameter after using some centralizers. When centralizers are not used, the $D_{ah}$ is usually smaller, like the left part. In this case, the
casing is more severely worn. After centralizers are used, the $D_{ab}$ will be significantly increased, like the right part. In this case, the wear on the casing can be reduced accordingly. However, a centralizer is usually installed every 3-5 casings during field construction. This is likely to lead to the distance between the two centralizers to be longer than the pitch. Therefore, installing centralizers on the casing string cannot completely avoid casing wear.

(3) Choosing the appropriate cementation method. According to the above analysis, the root cause of casing wear is lost circulation during casing running or cementing. In response to this problem, graded cementation can be used in this area. This method can reduce the length of the uncemented casing.

4. Conclusions and suggestions
(1) The root reason for intermediate casing wear in the Tarim oil field is that the effective inner diameter of the casing is smaller than the outer diameter of the tool joint after the uncemented casing helically buckled.
(2) The free casing is usually helically buckled after the casing string is hung, and the degree will be changed with different working conditions. Therefore, it is very important to accurately calculate the hanging weight.
(3) Too small hanging weight is the main cause of the helical buckling of the casing. Besides downhole high temperature and large hole diameter enlargement rate are also important factors.
(4) The main measures to reduce wear are increasing the hanging weight, installing centralizers, and using graded cementation.

5. References
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