

Study on the buckling behavior of continuous tubing column in deepwater natural gas hydrate reservoirs

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Abstract. Although the gas hydrate in the South China Sea has been successfully exploited, it is still in the exploration stage. In order to conduct large-scale commercial development, a large number of technical difficulties need to be overcome. The burial depth of the combustible ice in the South China Sea is more than 200 meters below the seabed mudline, and the vertical depth of the overlying strata that can be used for deflecting is small. The implementation of short radius horizontal wells has become the best technical means to ensure the drilling rate of the reservoir, increase the drainage area of the reservoir, and improve the development efficiency under the current technical conditions. Coiled tubing has more advantages than conventional drill string in the development of short radius horizontal wells because of its flexibility, which provides a new focus for cost saving. The buckling of coiled tubing is different from that of conventional rods. Its lateral displacement will be constrained by the size of the wellbore, resulting in sinusoidal and helical buckling. Therefore, it is very important to understand the downhole buckling behavior of coiled tubing for hydrate exploitation. In this paper, based on the previous research, the calculation model of coiled tubing buckling load is derived by using the energy method, and the load calculation method of straight well section is improved according to the rationality of finite element simulation, and then the critical buckling load of different well sections is analyzed; Considering the influence of hydrate decomposition in hydrate reservoir, assuming that the density of drilling fluid increases linearly with the well depth after the natural gas from hydrate decomposition enters the annulus, the average density formula of drilling fluid under different gas ratios at the top of the annulus is established, so as to obtain the calculation formula of coiled tubing floating weight and equivalent axial load under different gas ratios at the top of the annulus; The geometric nonlinear finite element buckling analysis model of coiled tubing is established based on the nonlinear large deformation theory, and the buckling process of coiled tubing under different axial loads and different top annulus gas ratios is simulated under different well sections.

Keywords: Coiled tubing, Critical buckling load, Hydrate decomposition, Finite element.

1. Preface

Natural gas hydrate is widely distributed in offshore continental shelf sediments and some plateau permafrost regions, with huge reserves, which can meet human energy needs for a long time. However, the technical difficulties in the economic exploitation of combustible ice have not been overcome. Now, if we can master the mining technology of combustible ice and realize large-scale economic mining of combustible ice, it will be of great significance to the future development of mankind. The research on natural gas hydrate basically stays on the dynamics of hydrate, while the research on the mechanics of coiled tubing from the decomposition of natural gas hydrate is relatively less.

Because the drill string is constrained laterally by the borehole, its buckling form is different from that of conventional rods. Therefore, scholars at home and abroad have adopted a lot of different methods to study its mechanical problems. In 1950, Lubinski^[1-2] gave the critical buckling load formula for sinusoidal buckling and helical buckling of drill string for the first time. In 1982, Mitchell^[3] simplified the drill string in the straight section as a slender beam for the convenience of calculation. According to the actual situation of the drill string in the wellbore, the constraint conditions were simplified as fixed end constraints, and the formula for the critical buckling load of the straight section was derived.

In 2016, Gong Yinchun^[15] took friction factors into consideration and carried out a study on downhole buckling behavior of pipe strings. In 2016, Xiang Lucky^[16] used ABAQUS software to simulate the buckling process of drill string in different well sections.

In 2019, Liu Qiong^[17] used cubic spline interpolation method to curve fit parameters such as well deviation angle, azimuth angle and well depth that describe spatial deflection shape of well trajectory. In 2020, Zhang Wenze^[19] used the energy conservation method and differential equation method to model and derive derivatives, and found that the derivation formula of CT critical bending was basically the same. In the same year, Hao Jiankun^[20] established the equilibrium differential equation of coiled tubing at different well depths by applying the theory of elasticity, solved the running friction and friction torque of coiled tubing, and established the running performance criteria of coiled tubing.

Therefore, through analyzing the characteristics of the South China Sea hydrate reservoir, combining with the coiled tubing drilling technology and considering the characteristics of deep-water drilling, this paper conducts a finite element analysis of the drill string buckling behavior during the drilling process, which provides a theoretical basis for the smooth drilling of natural gas hydrate reservoirs.

2. Coiled tubing buckling behavior

2.1. Description of buckling behavior

During the running of coiled tubing, due to the influence of self weight, friction and axial load at the bottom, bending will occur. Different loads will lead to different bending types, namely sinusoidal buckling and spiral buckling.

In the process of coiled tubing drilling, in order to overcome the friction resistance of the pipe wall and the axial pressure at the bottom, it is necessary to artificially apply downward axial pressure at the top of the coiled tubing on the ground. At this time, the coiled tubing can be regarded as a slender rod without transverse support fixed at the bottom. When the axial load at both ends of the compression section of the coiled tubing exceeds the critical buckling load, the coiled tubing will buckle. At the initial stage, because the axial load is small, the coiled tubing presents a sinusoidal waveform in the same plane. With the increase of the axial load, the coiled tubing will gradually transition from sinusoidal buckling to spiral buckling. If the axial load continues to increase when the critical spiral buckling is reached, the contact force between the coiled tubing and the wellbore will increase, thus increasing the friction resistance, which will eventually lead to the failure to transmit the axial force of the coiled tubing and the spiral self-locking.

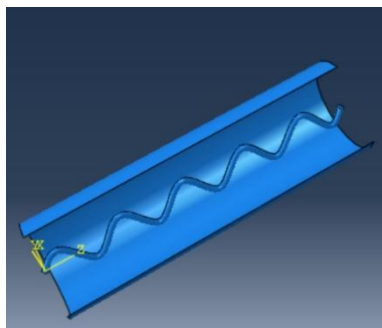


Figure 1. Sine Bending of Coiled Tubing in Wellbore

2.2. Basic assumptions

The buckling behavior of coiled tubing under actual working conditions is relatively complex, and the calculation of critical buckling load requires the following basic assumptions for coiled tubing:

- ① The borehole is cylindrical and the borehole wall is rigid;
- ② The coiled tubing is long enough without considering the influence of boundary conditions;

- ③ Torque has no effect on coiled tubing buckling;
- ④ The initial state of coiled tubing has no deflection, and it is simplified as a beam with the same properties along the length direction;
- ⑤ Ignore the influence of system fluid flow.

2.3. Buckling of coiled tubing in vertical well section

In the vertical well section, if the coiled tubing has no resistance during running, the coiled tubing will remain stretched. If there is resistance, the coiled tubing will be pressurized below the neutral point. If the axial load of the compression section exceeds the critical buckling load, buckling will occur.

Lubinski^[2] gave the calculation model of critical buckling load of coiled tubing in vertical well section without considering the influence of gravity.

At this time, the critical load at the bottom of coiled tubing is:

$$F_{cr, b} = \left(\frac{27EIq^2\pi^2}{16} \right)^{\frac{1}{3}} \approx 2.55(EIw_e^2)^{\frac{1}{3}} \tag{1}$$

The critical buckling load of the screw is calculated as:

$$F_{hel, b} = 5.55(EIw_e^2)^{\frac{1}{3}} \tag{2}$$

At this time, the critical load for sinusoidal buckling or spiral buckling is the axial force at the bottom, which is based on a fixed coiled tubing length, is $4EI\pi^2/q$. In fact, the length of the string is not fixed, so as L increases, the critical buckling load at the top of the coiled tubing with dead weight may be negative, that is, the upper end of the string is a tensile force.

2.4. Buckling of coiled tubing in horizontal well section

The initial state of the coiled tubing without bending is lying on the low side of the wellbore. As the axial pressure increases, when it exceeds a certain value, the coiled tubing will have a sinusoidal buckling shape. Continue to increase the axial pressure, at this time, the sine buckling will have a critical instability, and then the shape of spiral buckling will appear.

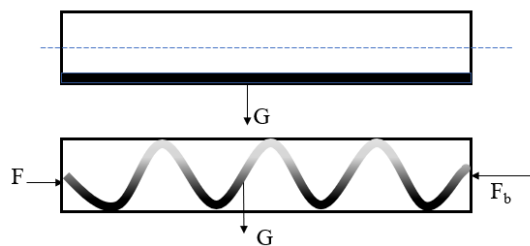


Figure 2. Coiled tubing in non buckling state and compression helical

$$F_{cr} = 2\sqrt{\frac{EIw_e}{r}} \tag{3}$$

2.5. Helical critical buckling load

The curve after coiled tubing spiral buckling can be described by the following equation:

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \\ \theta = 2\pi z / p \end{cases} \tag{4}$$

The pipe string shortening is related to the annular space gap and the screw pitch, and the formula is:

$$\delta=L\left(1-\frac{p}{\sqrt{p^2+4\pi^2r^2}}\right)\approx\frac{2\pi^2r^2L}{p^2} \tag{5}$$

So:

$$F=\frac{8\pi^2EI}{p^2}+\frac{w_e p^2}{\pi^2 r} \tag{1-6}$$

When $\frac{dF}{dp}=0$, The critical spiral buckling load of coiled tubing can be obtained:

$$F_{hel}=4\sqrt{\frac{2EIw_e}{r}} \tag{7}$$

3. Effect of hydrate decomposition on coiled tubing buckling

Hydrate will decompose to produce gas under the conditions of pressure reduction, heating and chemical agent addition. The escaping gas will enter the drilling annulus, which will reduce the density of annulus liquid, increase the internal and external pressure difference of coiled tubing, and then change the buoyancy of coiled tubing, thus affecting its buckling deformation. Therefore, it is necessary to study the influence of hydrate decomposition on coiled tubing buckling.

3.1. Effect of drilling fluid on buckling

The coiled tubing is always in the drilling fluid during drilling, so it will be subject to the buoyancy of the drilling fluid, which will affect the buckling of the coiled tubing.

The following is the fluid pressure distribution of the string in a straight well. From the external pressure P_o and the internal pressure P_i , the pressure increases with the depth of the well, and the force on the bottom is P_b . When the pressure loss of the bit nozzle is compared with the bottom pressure, it can be ignored, $P_{ib}=P_{ob}=P_b$.

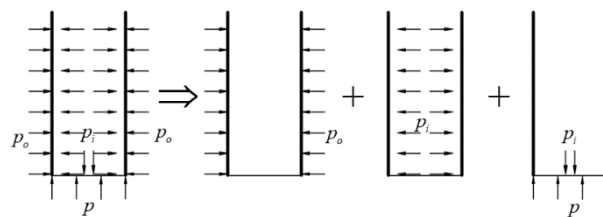


Figure 3. Fluid Pressure Distribution of Coiled Tubing

The fluid pressure at the bottom of the string will create axial pressure at the bottom of the string, which may cause the string to bend.

The virtual force is obtained by combining the above forces:

$$F_f=A_o(p_i-p_o) \tag{8}$$

The above two concentrated tension and pressure and the defined virtual force are actually determined not by the unbalanced forces S_o and S_i , but by the environment of the original hydrostatic fluid. For the straight pipe without buckling, these two forces will remain unchanged, and both forces in the vertical well are 0.

When the hydrate decomposes into the annulus during drilling, the density of drilling fluid in the annulus changes, and the internal and external pressures are no longer equal, the effective axial load is:

$$\begin{aligned} F_e &= F_m + F_h - F_{eq} \\ &= F_m + (A_o - A_i) p_0 - A_o p_0 + A_i p_i \\ &= F_m + A_i (p_i - p_0) \end{aligned} \quad (9)$$

3.2. Change rule of coiled tubing floating weight after hydrate decomposition

After the natural gas invades the annulus drilling fluid, because of the high bottom hole pressure, it initially exists as tiny bubbles with a small volume fraction, and the density of the drilling fluid at the bottom of the annulus is basically unchanged. As the pressure on the circulating bubble of drilling fluid decreases, the bubble becomes larger and its volume increases, and the density of drilling fluid decreases gradually, reaching the minimum value at the wellhead. Assume that the original drilling fluid density is, the density of ground drilling fluid after gas invasion is, and the bubble basically does not occupy the volume when the gas invades the annulus. Therefore, the density of drilling fluid at the bottom of the annulus can be regarded as the original drilling fluid density. Assuming that the gas proportion of ground drilling fluid is, then the density of ground gas invasion drilling fluid is:

$$\rho_d = (1 - V_g) \rho_m + V_g \rho_g \quad (10)$$

According to formula (3-26) and $\rho_i = \rho_m$:

$$w = w_s - \left(A_o - A_i - \frac{1}{2} V_g A_i \right) \rho_m g h \quad (11)$$

The unit line weight of coiled tubing is:

$$\begin{aligned} w_e = w/h &= (A_o - A_i) \rho_s g - \left(A_o - A_i - \frac{1}{2} V_g A_i \right) \rho_m g \\ &= (A_o - A_i) (\rho_s - \rho_m) g + \frac{1}{2} V_g A_i \rho_m g \end{aligned} \quad (12)$$

4. Coiled tubing buckling simulation

4.1. Basic parameters of the model

See Table 1 for structural parameters of wellbore and coiled tubing. The coiled tubing made of QT-16Cr is selected for the slender string, with a density of 7862kg/m³, a yield strength of 551MPa, an elastic modulus of 196.9GPa, a Poisson's ratio of 0.29, and a drilling fluid density of 1050kg/m³.

Table 1. Dimensions of wellbore and coiled tubing

Borehole diameter (mm)	Outer diameter (mm)	Wall thickness (mm)
215.9	127	9.20

(1) Modeling method: Use the component module to create the basic component, assign the component attribute parameters after the component is created, then assemble and apply the boundary conditions, and finally perform the mesh finite element calculation.

(2) Model unit: The length of each well section is 100m. Considering that the parameters of the coiled tubing are consistent everywhere, the coiled tubing is discretized into beam elements, and the well wall is regarded as a rigid body. Discrete rigid elements are used.

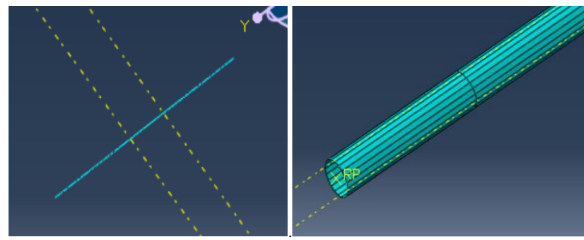


Figure 4. Coiled tubing and well wall gridding

(3) Boundary condition:1. Displacement constraint: The top displacement of coiled tubing is fully constrained, the bottom axial is not constrained, and the wellbore is fully constrained. An initial displacement of 0.1mm in X direction is added at 2m from the top of the coiled tubing in the vertical well section, and no initial displacement disturbance is set in the curved well section and horizontal well section.2. Load constraint:The coiled tubing is subject to its own gravity, drilling fluid buoyancy and axial load.

(4) Assumptions:It is assumed that the initial state of the coiled tubing is coaxial with the wellbore. When the coiled tubing contacts the wellbore during loading, the coiled tubing is restrained by the normal and tangential force (friction) of the wellbore, and the friction coefficient is taken as 0.3. The borehole rigidity does not deform.

4.2. Buckling modulus of vertical well section

(1) Buckling simulation results without considering the influence of drilling fluid buoyancy

Since the deformation is very small compared with the length of coiled tubing, the horizontal deformation of coiled tubing is magnified by 100 times to facilitate the observation of deformation. It can be seen from the figure below that when the axial load at the bottom end is 5kN, the upper end of the coiled tubing is basically in a stable state, and the lateral displacement at the lower end is in the same direction, which is only compression bending, and does not form a sinusoidal buckling shape. When the axial load increases to 11kN, the coiled tubing basically presents a complete sinusoidal waveform. As the load continues to increase, when the load is 19kN, large displacement occurs in both X and Y directions, Gradually transition to spiral buckling. When the load increases to 25kN, it can be clearly seen that the coiled tubing presents a complete spiral waveform.

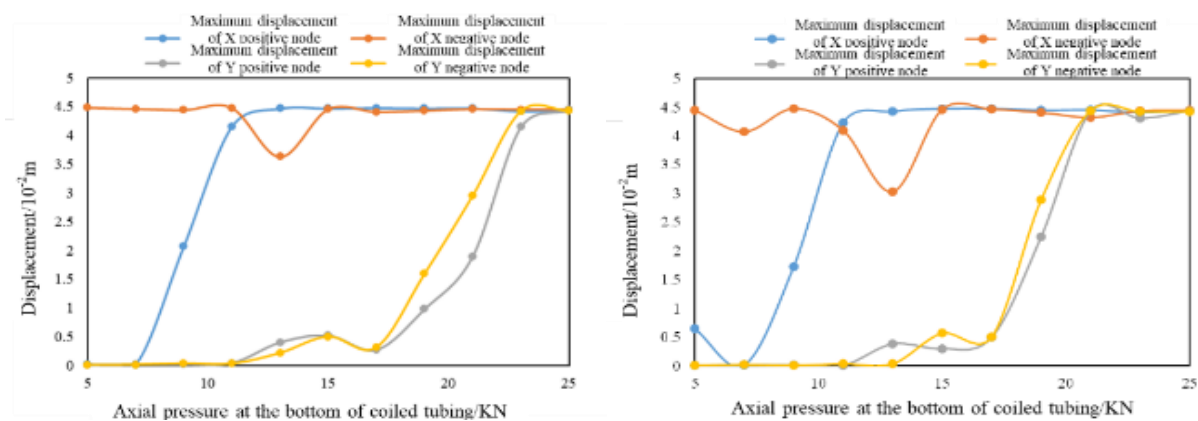


Figure 5. Node Displacement of Coiled Tubing under Different Axial Loads

(2) Buckling simulation results considering the influence of drilling fluid buoyancy

It can be seen from the figure below that when the axial load at the bottom end is 5kN, the coiled tubing is basically in a stable state. When the axial load increases to 11kN, the coiled tubing basically presents a complete sine wave. With the continuous increase of the load, when the load is 19kN, both X and Y directions show a large displacement, and gradually transition to spiral buckling. When the load increases to 21kN, it can be clearly seen that the coiled tubing presents a complete spiral wave.

(3) Coiled tubing buckling under different gas ratios of drilling fluid at the top of annulus

It can be seen from the previous chapter that under different gas ratios at the top of the annulus, the buoyancy of the coiled tubing is different from that of the drilling fluid, so its critical buckling load will also change. By using the finite element simulation software, set the floating weight values of different coiled tubing to simulate different gas ratios, change the axial load, and observe the buckling of the coiled tubing.

When the hydrate is not decomposed and the gas proportion at the top of the annulus is 0, the density of drilling fluid in the annulus and coiled tubing is the same. This is an ordinary drilling process. The buoyancy of the coiled tubing is the weight minus the buoyancy of the drilling fluid; When the combustible ice decomposes into the annulus and the proportion of gas increases, the density of annular drilling fluid is lower than that of the drilling fluid inside the coiled tubing, the floating weight of the coiled tubing changes, the floating weight gradually increases, and the critical buckling load of the coiled tubing increases.

4.3. Comparison between simulation results and theoretical results

4.3.1. Vertical well section

It can be seen from the following table and figure that the error between the simulated value of the critical load of sinusoidal buckling and spiral buckling of the vertical well section and the theoretical value is less than 5%, and the simulation results have high reference value.

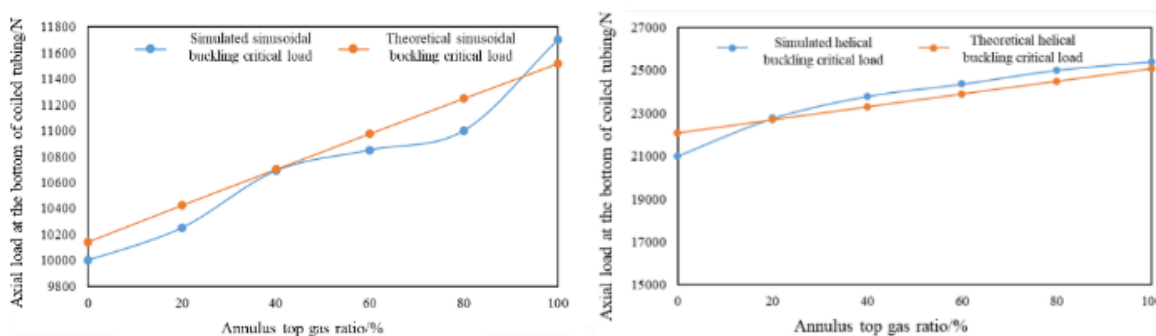


Figure 6. Comparison of sinusoidal critical buckling load under different gas proportions

4.3.2. Horizontal well section

There is a big difference between the simulation results of sinusoidal buckling in horizontal well section and the theoretical results. The reason may be that the axial load is too large, and the critical load of sinusoidal buckling is not easy to determine, with an error of 10-20%; The simulation results of spiral buckling are generally less than the theoretical calculation values, and the error is not more than 15%. In general, the finite element simulation results of the horizontal section are feasible.

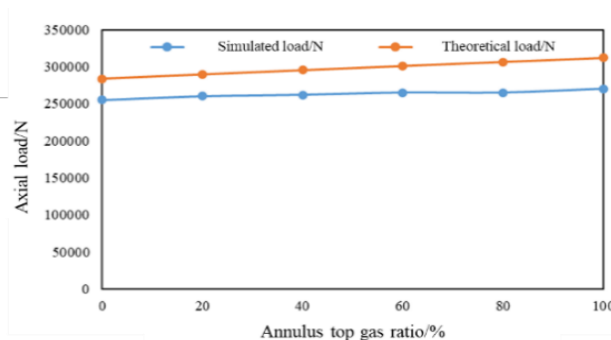


Figure 7. Comparison Diagram of Helical Critical Buckling Loads under Different Gas Proportions

It can be seen from the above simulation results that the finite element simulation can reflect the buckling characteristics of coiled tubing under certain conditions. Therefore, the next step is to conduct buckling simulation for the actual hydrate reservoir and explore the buckling behavior of coiled tubing in the drilling of hydrate reservoir.

4.4. Summary of this chapter

In this chapter, the finite element analysis model of force and deformation of large deformation coiled tubing is established, and the ABAQUS software is used to simulate the buckling of 215.9mm wellbore, 127mm coiled tubing vertical section, bending section and horizontal section, and the following understandings are obtained:

(1) With the increase of axial load, sinusoidal buckling and helical buckling will occur successively in the vertical and horizontal segments; The transition process between sinusoidal buckling and helical buckling in the vertical segment is obvious, while the boundary line between sinusoidal buckling and helical buckling in the horizontal segment is not easy to distinguish.

(2) The buckling of coiled tubing under different annular top gas proportions is simulated. The simulation results show that the decomposition of hydrate will increase the sinusoidal and helical critical buckling loads of coiled tubing, which is consistent with the theoretical analysis.

(3) The critical buckling loads of the vertical and horizontal sections are obtained through finite element simulation. Compared with the analytical solution, the error values of the sinusoidal buckling and spiral buckling of the vertical well section are within 10%. However, in the horizontal well section, the error values of the simulated critical sinusoidal buckling are not easy to determine, so the error is about 15% - 20%, and the error of the spiral critical buckling load is 10% - 15%. This shows that the finite element simulation method is feasible for the buckling analysis of coiled tubing.

5. Conclusion

(1) The decomposition of hydrate will cause the natural gas to enter the drilling annulus, resulting in the difference in the density of drilling fluid inside and outside the drill string. With the increase of the decomposition amount of hydrate, the resultant force of the internal and external fluid pressures on the coiled tubing may be negative, that is, the force of fluid added to the coiled tubing is vertical downward, in the same direction as gravity.

(2) The finite element analysis model of force and deformation of large deformation coiled tubing is established, and the buckling simulation of vertical section, bending section and horizontal section of coiled tubing is carried out by using ABAQUS software. The simulation results show that:

① Without considering the buoyancy of drilling fluid, with the increase of axial load, the vertical section and the horizontal section will successively appear sinusoidal buckling and spiral buckling;

② The transition process between sinusoidal buckling and helical buckling in the vertical segment is obvious, while the boundary line between sinusoidal buckling and helical buckling in the horizontal segment is not easy to distinguish;

③ The decomposition of hydrate will increase the sinusoidal and helical critical buckling loads of coiled tubing, so the decomposition of hydrate will inhibit the buckling of coiled tubing.

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