Weak Point Analysis of Deepwater DST String in Service

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Abstract. Considering the deepwater test technology, in this study, temperature and pressure loads of deepwater drill-stem tested (DST) string in string deployment, pressure perforation, flowing test, and shut-in well stages are evaluated. In view of the large displacement and contact problem, a mathematical model is established for the deepwater DST string system to assess the weak point based on nonlinear contact theory. The results show that the temperature and internal pressure of DST string are mainly determined by test production in the flowing test stage. The pressure perforation and shut-in well stages are more risky for DST string in water, whereas the string deployment and shut-in well stages are more risky for DST string in downhole. With increasing test production, the stress level of DST string decreases in water and increases in downhole as a whole. Extra attention should be paid to the string units adjacent to the top, lower flex joint, hanger, and packer, which are the strength weak points of deepwater DST string. The weak point assessment method provides powerful support for operation risk management and decision-making of DST string in offshore test process.

1. Introduction

Deepwater testing is an extremely important process in marine petroleum and natural gas exploration for timely detection and accurate evaluation of deepwater reservoirs. Deepwater drill-stem tested (DST) string is the key equipment; its security directly relates to the success of testing operation and economic efficiency of entire project. Thus, weak point assessment for deepwater DST string has a positive effect on the security of offshore testing.

The risk analysis and control technology of deepwater DST string system have been studied for a long time [1,2]. However, previous studies about mechanical model and structure weakness have primarily focused on drilling riser [3] or downhole string [4]. There has been little research on the weak point assessment of a deepwater DST string in service at present. Xie et al. conducted a mechanical analysis of DST string based on the equivalent composite model [5]. But, the study ignored the effect of contact between DST string and riser. Liu et al. evaluated the warning control boundary of platform drift distance for a deepwater DST string based to nonlinear finite element model [6]. Meng et al. developed a sealing weak point analysis method for deepwater DST string [7]. However, this study failed to consider the effect of deepwater testing process and evaluate the strength weak point of a DST string under typical operation modes in service.

In this study, a coupling analysis model of deepwater DST string system is established. Based on the temperature and pressure load verified by test technology, the mechanical behaviour of deepwater DST string is studied in typical operation stages. Then, the strength weak points of a DST string are determined, and the effect of test production on the stress distribution of DST string is discussed.
2. Operation analysis

As shown in Figure 1, deepwater testing is usually performed on a floating platform. The riser is connected from the sea level to casing through a wellhead, forming a circular channel of testing fluid. The DST string in a riser or casing contains drill stem, centralizer, test tree, hanger, seal assembly and so on. They all build up the channel transporting natural gas from reservoir to platform with the function of measuring and controlling test parameters.

![Figure 1. Physical model of deepwater DST string system.](image)

A deepwater DST string system is not only subjected to various external loads (e.g., current, temperature, and pressure) in service, but also subjected to process load and contact load between the outer and inner strings. In offshore test process, the DST string system has four typical stages.

① String deployment stage: The riser is in the connection state with testing fluid inside. The DST string is connected with the platform hanging device running to the reservoirs. The internal pressure and annular pressure of DST string are equal to the hydrostatic pressure of testing fluid.

② Pressure perforating stage: First, the internal pressure is reduced to protect the reservoir. Then, the annular pressure is increased to open the tester valve from the auxiliary lines near the blowout preventer. Finally, the perforation gun is detonated by adding internal pressure from the rotary table.

③ Flowing test stage: The annular pressure remains constant after perforating. The internal liquid is natural gas, and the external liquid is testing fluid. The sustained temperature and internal pressure of DST string are significantly affected by the formation fluid.

④ Shut-in well stage: The internal formation fluid and external testing fluid are both in a steady state. For the prevention of natural gas hydrate, internal pressure is reduced to zero. The temperature of DST string changes to a steady state through heat exchange.

3. Analysis model

3.1. Mechanical Model

Deepwater DST string system belongs to slender and flexible string. Generally, the factors affecting the axial stress state of a DST string includes ballooning effect, piston effect, temperature effect, axial load, contact force and so on. The mechanical analysis model of downhole string provides important reference for this paper[8]. Considering the DST string is composed of linear elastic homogeneous pipe elements with small deformation, the lateral mechanical model can be presented as:
\[
EI \frac{d^4 y}{dz^4} + T(z) \frac{d^2 y}{dz^2} + w(z) \frac{dy}{dz} = F(z)
\]  

(1)

where \( E \) is the elastic modulus, \( I \) is the moment of inertia, \( y \) is the horizontal displacement, \( z \) is the vertical height, \( T \) is the effective tension, \( w \) is the mass per unit length, \( F \) is the transverse load.

The differential equation of riser is the same as shown in Eq.(1). However, the main lateral force of riser is generated by sea wave and ocean current. The combined wave and current force can be calculated using Morison’s equation \(^9\):

\[
F_{\text{ocean}}(z) = 0.5C_D\rho D_R^2 (v_w + v_c) \left| v_w + v_c \right| + 0.25C_m \rho \pi D_R^2 a_w
\]

(2)

where \( C_D \) is the drag force coefficient; \( C_m \) is the inertia force coefficient; \( \rho \) is the density of seawater; \( D_R \) is the outer diameter of riser; \( v_w \) is the horizontal velocity of sea wave particle; \( v_c \) is the current velocity; \( a_w \) is the horizontal acceleration of sea wave particle.

Direct modelling of structure interaction is applied to study the weak point of DST string in riser or casing, as shown in Figure 2. The outside circle represents riser or casing; the inside circle represents DST string; the green area between them represents the gap element to constrain the pipe-in-pipe contact between the outer and inner strings. The contact force is generated when the distance between red and blue areas decreases to zero.

\[\begin{align*}
R_i &= 0; f_i = 0 & \left| \frac{1}{2}(d_i - D_l) - \overline{r} \right| & \geq \varepsilon \\
R_i &\geq 0; f_i = \mu \cdot R_i & \left| \frac{1}{2}(d_i - D_l) - \overline{r} \right| & < \varepsilon
\end{align*}\]

(3)

where \( R_i \) and \( f_i \) represent the normal reaction and friction between DST string and riser/casing; \( d_i \) and \( D_l \) are the inner diameter (ID) of outer string (riser or casing) and outer diameter (OD) of inner string (DST string) on the \( i \)th gap elements; \( \overline{r} \) is the change in position corresponding to the \( i \)th gap element; \( \varepsilon \) is a small value and usually between \( 10^{-4} \sim 10^{-5} \); \( \mu \) is the friction coefficient.

3.2. Boundary conditions

The top end of the DST string system is connected with a platform. The top tension of the outer riser and inner DST string are from the tensioner and hook, respectively. Considering the security of emergency disconnect, the top tension is recommended to use the method based on the residual tension at bottom from the French institute:

\[
T_{\text{top}} = \sum_{y=0}^{k} (W_{\text{string}} + W_{\text{fluid}}) + RTB
\]

(4)
where $W_{\text{string}}$ is the effective weight of DST string or riser in water; $W_{\text{fluid}}$ is the weight of testing fluid for riser or formation fluid for test string in water; $RTB$ is the residual tension at subsea wellhead, in this study we set $RTB = 0.1 \text{ MN}$ for DST string and $RTB = 0.2 \text{ MN}$ for riser.

The bottom end of DST string is free in downhole. Because of the varied pressure with internal and external pressure, the bottom end of DST string will be acted by piston force, as shown in the local enlarged structural drawing of Figure 1. The effect acting the end of DST string with pressure change can be obtained by [9]:

$$F_a = (A_{so} - A_i) \cdot P_i - (A_{so} - A_o) \cdot P_o$$

where, $A_{so}$ is the inner diameter of packer; $A_i$ and $A_o$ is the inner diameter and outer diameter of DST string, respectively; $P_i$ and $P_o$ is the internal and external pressure of seal assembly in the packer.

The integrated procedure for weak point analysis of deepwater DST string in service is summarized as follows: (1) collect the basic information, such as string configuration, environmental parameter, reservoir properties, operation scheme and so on; (2) analyse temperature and pressure distribution in the DST string [10] during the four typical stages; (3) conduct other external load and boundary analysis of the DST string; (4) establish the mechanical model of the deepwater DST string system; (5) conduct numerical simulations under different operation stages and acquire the axial stress, hoop stress, radial stress and von Mises stress of the DST string; (6) draw the stress distribution curve and determine the weak points of the DST string in water and downhole.

4. Case study and discussion

4.1. Basic data and load analysis

Taking a deepwater well in China as an example, the basic parameters are as follows: the water depth is 1500 m; the sea surface tide velocity is 0.345 m/s; the wave height is 2.2 m; the wave period is 5.9 s; the well depth under mud line is 2015 m; the testing fluid density is 1350 kg/m$^3$; the relative density of nature gas is 0.62; specific heat of natural gas, sea water, and steel are 2227, 4180, and 400 J/(kg•°C); heat conduction coefficient of natural gas, sea water, and steel(test string and riser) are 0.03, 0.57, and 43.26 J/(m•°C), respectively. The configuration of DST string is shown in Table 1.

| Components           | OD (in) | ID (in) | Top Position (m) |
|----------------------|---------|---------|------------------|
| Oil tube             | 4.5     | 0.56    | 1504.00          |
| Centralizer          | 16      | 6.5     | 1482.20          |
| Lubricator valve     | 12.5    | 4.75    | 1481.23          |
| Oil tube             | 4.5     | 0.56    | 1477.81          |
| Centralizer          | 16      | 6.5     | 753.33           |
| Oil tube             | 4.5     | 0.56    | 752.36           |
| Centralizer          | 16      | 6.5     | 12.88            |
| Retainer valve       | 12.5    | 4.75    | 11.91            |
| Oil tube             | 4.5     | 0.56    | 8.18             |
| Subsea test tree     | 13.8    | 5.38    | 5.46             |
| Oil tube             | 4.5     | 0.56    | 4.17             |
| Hanger               | 13      | 3       | 2.62             |
| Oil tube             | 4.5     | 3.374   | 0.85             |
| Methanol injection joint | 8.25 | 3        | -603.20          |
| Oil tube             | 4.5     | 3.374   | -604.53          |
| Oil tube             | 4.5     | 3.374   | -1747.98         |
| Oil tube             | 4.5     | 3.374   | -1795.73         |
| Safety valve         | 5       | 2.25    | -1803.29         |
| Locator              | 7.06    | 4.75    | -1803.92         |
| Seal Assembly        | 5.97    | 4.75    | -1803.92         |

The case study includes four test productions, namely, $1.25 \times 10^4$, $2.92 \times 10^4$, $5.00 \times 10^4$ and $6.25 \times 10^4$ m$^3$/h. Figure 3 shows the environment temperature at sea level is 25°C and deceases along the water depth, whereas the lowest temperature at mud line is 3°C. The formation temperature increases linearly along the well depth and the maximum value appears at the bottom. The temperature of DST string is mainly determined by the test production in flowing test stage and the temperature of the bottom string equals to the bottom hole temperature (93°C). As shown in Figure 4, the annulus
The internal pressure of DST string at the bottom matches the bottom hole pressure (45 MPa), and a linear decrease trend from bottom to top is observed. The test production is the main factor for the decrease in the slope of internal pressure.

Figure 3. Temperature distribution of DST string. Figure 4. Pressure distribution of DST string.

4.2. Weak point analysis on DST string in water

Supposing the drift distance of platform is 30 m, the stress distribution of DST string is analysed based on the proposed model. Figure 5 shows a linear decrease of the von Mises stress of DST string in water during string deployment stage, pressure perforating stage, and flowing test stage (5.00×10⁴ m³/h). A cambered decrease is observed in the shut-in well stage. During all the stages, the von Mises stress of DST string in water changes rapidly at the area of upper, middle, and lower centralizer where the cross-area change. The stress significantly increases due to the sharp increase in bending moment at the top of DST string and lower flex joint (LFJ). The pressure perforating and shut-in well stages are the dangerous stages for the DST string in water. The weak points of DST string in water are found to be the string units adjacent to the top and the LFJ where special attention is needed during detection and maintenance.

Figure 5. Von Mises stress of DST string in water during four typical stages. Figure 6. Von Mises stress of DST string in water under different productions.

The difference between the internal and external pressure, and the change in temperature are small in the string deployment stage; therefore, both the hoop stress and radial stress of DST string are close to zero. The stress level of DST string in string deployment stage is the smallest in the four stages. Compared to the string deployment stage, a certain pressure (e.g., 35 MPa) is applied at the inside of DST string from rotary in the pressure perforating stage. The higher internal pressure leads to a higher von Mises stress. In the shut-in well stage, the internal pressure becomes the hydrostatic of formation fluid, and even reduces to zero. The imbalance between internal and external pressure leads to a great
change in the state of stress. Because the pressure difference gradually increases at the bottom, a slight increase in von Mises stress is observed in the shut-in well stage.

The effect of DST string in water from test production is obtained, and the result is shown in Figure 6. The DST string stress decreases with the increasing test production. There are two main reasons leading to this change: (1) with the increase of production, the DST string temperature increases, and the following thermal expansion reduces the axial force; (2) the internal pressure is always higher than the external pressure for DST string in water during the flowing test stage. The internal pressure of DST string drops while the external pressure remains stable with the increase of test production. The difference between the internal and external pressure decreases leading to a smaller von Mises stress.

4.3. Weak point analysis on DST string in downhole

The stress distribution of downhole DST string is shown in Figure 7. A linear decrease of the von Mises stress is observed in downhole DST string during string deployment stage. A cambered increase or decrease is observed in the pressure perforating stage, flowing test stage \((5.00 \times 10^4 \text{ m}^3/\text{h})\), and shut-in well stage. The von Mises stress significantly increases at the bottom due to the piston effect during the above mentioned three stages. During all the stages, the von Mises stress of downhole DST string changes rapidly at the area of methanol injection joint, sampling head, and safety valve where the cross-area change. The string deployment and shut-in well stages are the dangerous stages for the DST string in downhole. The weak points of downhole DST string are found to be the string units adjacent to the hanger and packer.

The effect of downhole DST string from test production is obtained, and the result is shown in Figure 8. A cambered decrease as a whole and a slight increase at bottom are observed in stress curves of downhole DST string under different test productions. This is because the piston effect provides an upward force to the bottom of downhole DST string during flowing test stage. With the change of test production, the temperature of downhole DST string change little. So, the piston effect becomes the main factor of stress state for downhole DST string. For the piston effect decreases with the increasing test production, the downhole DST string stress increases with the increasing production.

5. Conclusions

In view of the large displacement and contact problem, an analysis model is established for deepwater DST string system to assess the weak point. Based on the temperature and pressure load confirmed by deepwater test technology, the weak points of DST string under typical operation stages are confirmed. The pressure perforation and shut-in well stages are more risky for DST string in water, whereas the string deployment and shut-in well stages are more risky for DST string in downhole. The string units adjacent to the top, lower flex joint, hanger, and packer are the strength weak points of deepwater DST string system where special attention in detection and maintenance is needed.
The model proposed in this paper has been successfully applied in a deepwater testing operation and has guided preliminary hazard analyses and maintenance for the deepwater DST string in the South China Sea.

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