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ANALYSIS ON INSTALLATION PROCESS OF THE SUBSEA VERTICAL TREE BASED ON SEA EXPERIMENT

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ABSTRACT

In order to promote the local production of subsea vertical tree, a study is launched based on the sea experiment of subsea vertical tree prototype. Through the analysis of the structural features of subsea vertical tree and its installation methods as well as the combination with existing related standards and researches at home and abroad, the requirements are put forward which are needed in the installation and testing process, the installation schemes of sea experiment are designed, the installation procedure is formulated, while the displacement and stress condition of drill pipe are analyzed during the installation process with Drill Pipe Installation Method. The study result will provide a reference for the sea experiment operation of domestic subsea vertical tree and related subsea production equipment.

Key Words: installation technologies; subsea vertical tree; sea experiment operation; Mechanical analysis

Introduction

With the increasing demand of energy throughout the world, the onshore oil and gas resources have been far from enough to meet the demands, so that offshore oil and gas exploration and exploitation have become strategic emphasis for achieving energy sustainable development in China[1]. Subsea tree is key equipment in the subsea production system of offshore oil and gas. Development of subsea tree has been started at abroad since the 1960s, and the installation and testing technologies of subsea tree have been becoming mature. In recent years, correlation techniques of subsea tree have been researched in China, while the researches of testing technologies mainly concentrate on testing onshore and in the shallow water, and sea experiment of subsea tree has not been reported. Sea experiment is the indispensable part during the research and development process of subsea tree, aiming at testing the air tightness of the sealing surface or the connectivity and air tightness of joint after installation in the marine environment, testing the installation feasibility in non-fixed operating and under the effect of wave and flow, and testing the operability of ROV under the wave-current interaction as well as the function of test valve and actuator in sea conditions, which is a necessary procedure for verifying prototype performance and function. This paper mainly studies key technologies of sea experiment of subsea vertical tree and the detailed installation and testing program of sea experiment.

1 Research Status of Sea Experiment on Subsea Tree

Early in the 1970s, sea experiment of subsea production system has been conducted at abroad[2-4]. In 1975, Exxon conducted sea experiment on the researched subsea production system under water with a depth of 51 meters in the Gulf of Mexico (Fig. 1), installing with drilling riser and testing the pipeline connection and the tree function. In 1981, sea experiment of a subsea production system developed by 6 oil companies like AGIP and Chevron was conducted in the west coast of Norway, mainly testing the connection of tree pipeline; non-diving operation was adopted in the entire installation process with the aid of ROV. In 1983, E.J. OBrien, P.Joubert and B.R.Krist-offersen et al. conducted sea experiment on the developed high-pressure flexible pipe (Fig. 2); the depth of the sea experiment was about 106 m, and cable laying method was used. In 2003, Robert Voss et al.[5] introduced the basic structure of horizontal tree and its installation process, and discussed the installation steps and installation tools of the horizontal tree system.

The main study at home has been focused on deep-water installation of horizontal tree and subsea manifold. In 2013, Gong Mingxuan et al.[6] analyzed the laying-down and installation process of subsea horizontal tree. In 2014, Xiao Yiping et al. [7] introduced the order of installation and requirements of subsea horizontal tree. In 2011, aiming at the installation problems of subsea manifold in the deep and ultra-deep water, Wang Yingying and Duan Menglan et al.[8] analyzed the adaptability of three kinds of installation methods in the installation process, namely hoisting method, pulley method and downswing method. In 2014, Fu Jianbo and Su Feng et al. [9] proposed the installation method and selection principles of manifold in the comprehensive consideration of safety and reliability. Relevant literature and standards of sea experiment on subsea tree have not yet been seen in China. In this paper, the installation and testing methods of sea experiment of subsea vertical tree are studied. The difference between sea experiment and actual installation and testing process is that simplified installation method is designed, and program without blowout preventer and drilling riser is adopted, so that it is more economical and much better to operate while achieving the same installation and testing results.

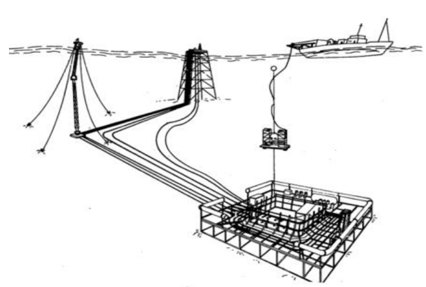

Figure1 Sea Experiment of Exxon

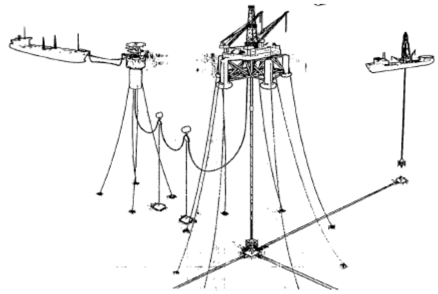

Figure2 Sea Experiment of Large, High-Pressure Flexible pipe

2 Sea Experiment Process of Subsea Vertical Tree

2.1Introduction of Subsea Vertical Tree

Subsea vertical tree is mainly used in the oil and gas fields in which frequent removal of tube is unnecessary for workover job. The tube hanger is locked in the well head, the tree is placed on the well head, and the connector locks the tree body with the well head. Structure of typical subsea vertical tree is shown in Fig. 3.

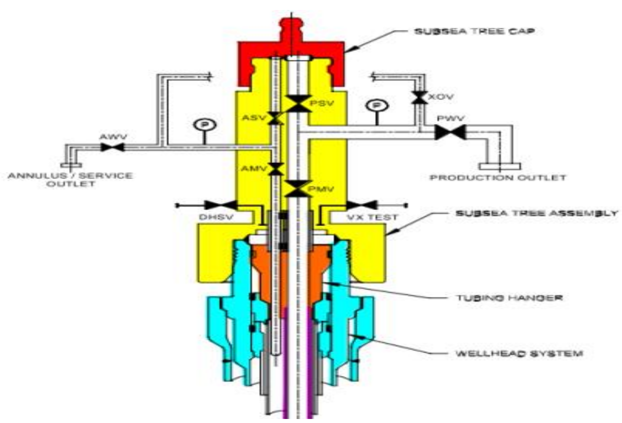

Figure3 Structure of Subsea Vertical Tree

2.2Sea Experiment Process

By analyzing the relevant standards of the oversea subsea production system[10-12] and the installation method of subsea horizontal tree, installation and testing procedure of subsea vertical tree in sea experiment is designed as shown in Fig. 4.

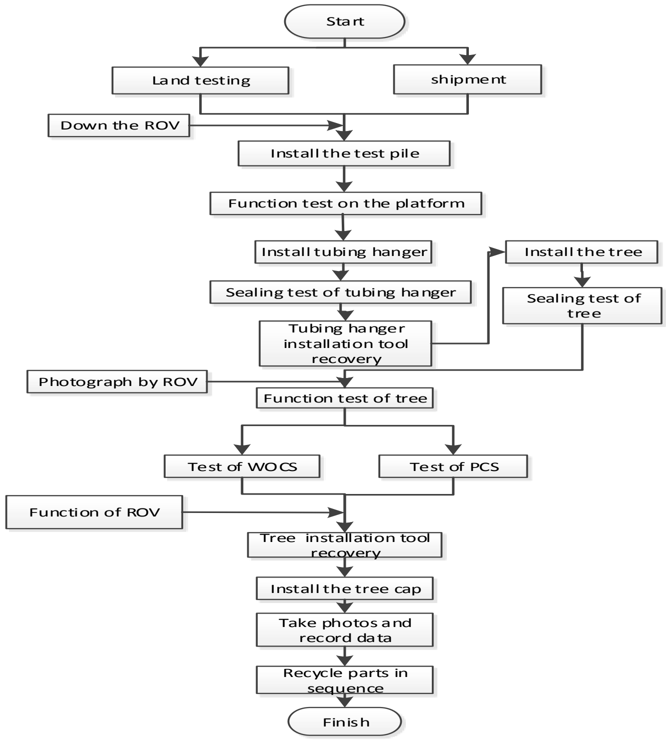

Figure4 Installation and Testing Process of Sea Experiment on Vertical Tree

3 Selection of Lowering Methods

The laying ways of subsea tree body mainly contain: cable installation, drill pipe installation and drilling riser installation. Water depth is the main factor in selecting the laying method of subsea tree. In the shallow water, wire rope is often used for laying-down, and in the deep water, drill pipe installation or work over riser installation is usually adopted to ensure the axial and radial departure of the installation equipment; the drilling riser installation is mainly for the installation environment with depth over 500m. In this subject, the water depth of sea experiment is set as 100m, using drill pipe installation (Fig. 5).

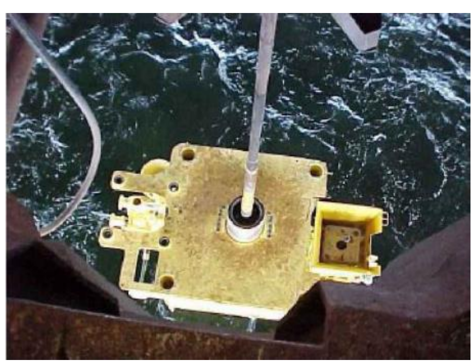

Figure5Installation of Drill Pipe

4 Mechanical Analysis of Installation Process

4.1Main Installation Stage of Subsea Tree

In the laying and installation process of subsea tree, the environment is extremely complex, which is influenced not only by sea currents and waves, but also by the upper platform motion. The whole installation process is very complicated. In different installation stages, the environmental loads and boundary conditions are different. Through the understanding of the laying and installation technique of subsea tree, the installation process is simplified to several main stages as shown in Fig. 2-6.

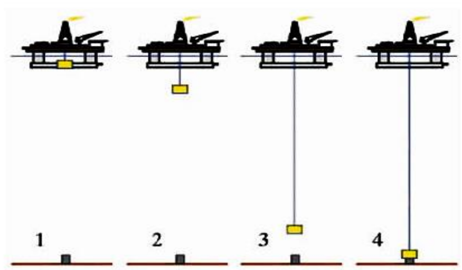

Figure 6 Four Stages of the Installation of Subsea Tree

In this paper, directing at the third stage (laying from 10m below the sea surface to 10m above the wellhead) with unguided installation of drill pipe moonpool, mechanical analysis is conducted on the drill pipe and the tree system. The environmental loads in this stage are mainly the current loads and the wave loads, so that the mechanical analysis model can be established, and finally the model can be solved by using MATLAB.

4.2 Theoretical Assumption

In the laying and installation process of subsea tree in the third stage, the stress of the drill pipe and tree system is complicated. In order to facilitate the theoretical research, the following assumptions are made:

1) Suppose that the riser material is uniform and isotropic, and it is always within the linear elastic range during motion and deformation.

2) Because the ratio between the diameter and the length of drill pipe is extremely small, it mainly bears lateral load, and the deformation mainly lies in bend. Therefore, the riser is assumed as hanging stick for mechanical analysis.

3) Suppose that the motion of currents, waves, drill pipes and tree are in the same layer, and the lift force of currents is not taken into account.

4) Coupled motion of platform is not considered in this study.

4.3Calculation of Current Loads

Since the velocity of current (mainly wind current) varies slowly over time, the current is often seen as a stable flow in engineering design, which means the current force on the structure is regarded as a drag force. In the laying and installation process of the tree, the force of current on the drill pipe and the tree can be equivalent to the drag force (flow resistance). In accordance with the norms of China Classification Society, it should be calculated as follows.

(1) The current force acting on the unit length of the drill pipe can be expressed as:

$$f_c = \frac{1}{2} C_D \rho_w D {v_c}^2 \quad (4\text{-}1)$$

In the formula,

C_D——horizontal drag force coefficient of cylindrical body;

ρ_w——the density of sea water, kg/m^3;

D——outer diameter of cylindrical body; m;

v_C——current velocity from the bottom of the sea, m/s.

(2)Conclusion can be obtained from the formula (4-1) that the current force needs to be calculated according to the current velocity. If the current force of the whole drill pipe is needed, the current velocity at each depth under water is required. However, the current velocity is changed with different depth of sea water, and the marine environment is complex and changeable, so that it is difficult to measure the current velocity of each depth. Therefore, ideal condition should be assumed, and the current velocity at a certain depth can be approximately calculated according to the formula used by the US Shipping Registering Bureau.

$$v_c = u_1 (\frac{d}{h})^{\frac{1}{7}} + u_2 (\frac{d}{h}) \quad (4\text{-}2)$$

In the formula,

u_1——tidal current velocity at the sea surface, m/s;

u_2——current velocity at the sea surface, m/s;

d——the depth from the calculation depth to the bottom of the sea, m/s;

h—— the depth of the water, m.

(3) the current force on the tree

According to formula (4-1), the area of thrust surface of the laying-down drill pipe is replaced by the current-force area of the tree, and:

$$f_C = \frac{1}{2} C_D \rho_w A v_C^{\ 2} \quad (4\text{-}3)$$

In the formula, *A* refers to the projected area of the tree in the flow direction.

4.4Calculation of Wave Loads

At present, the calculation of wave loads mainly adopts the Morsion equation. This theory assumes that the existence of cylindrical body has no obvious effect on the wave motion, and regards that the effect of the wave on the cylindrical body is mainly caused by the viscous effect and virtual mass effect.

According to the Morsion equation, the formula of wave force is:

$$f_w = f_D + f_I = \frac{1}{2} C_D \rho_w D u |u| + \frac{\pi}{4} C_M \rho_w D^2 \frac{d_u}{d_t} \quad (4\text{-}4)$$

In the formula,

f_w——horizontal drag force on the unit length of the cylindrical body, kN/m;

f_I——horizontal inertia force on the unit length of the cylindrical body, kN/m;

D——projected area of the unit length of the cylindrical body perpendicular to the direction of wave propagation, m^2;

u——horizontal velocity of water particles perpendicular to the axis of the cylindrical body,m/s;

$\frac{d_u}{d_t}$——horizontal acceleration of water particles perpendicular to the axis of the cylindrical body; m^2/s.

Airy Wave Theory is used to calculate the horizontal velocity u and horizontal acceleration $\frac{d_u}{d_t}$ of the water particles in the deep water, namely:

$$u = \frac{\pi H}{T} e^{\left[\frac{2\pi(x-d)}{L}\right]} \cos 2\pi \left(\frac{y}{L} - \frac{t}{T} \right) \quad (4\text{-}5)$$

$$\frac{d_u}{d_t} = \frac{2\pi^2 H}{T^2} e^{\left[\frac{2\pi(x-d)}{L}\right]} \sin 2\pi \left(\frac{y}{L} - \frac{t}{T} \right) \quad (4\text{-}6)$$

In the formula,

H ——wave height, m;

T ——period, s;

L ——wave length, m.

4.5 Joint Action of Waves and Currents

In the actual marine environment, sea currents exist as well as waves, and sea currents would change the motion characteristic of waves, so that the joint action of waves and currents is very complex. In the calculation of the environmental loads under the joint action, the expression is:

$$F=\frac{\rho_w}{2}C_D D\left(v|v|+u|u|\right)+\frac{\pi}{4}\rho_w C_M D^2\left(\frac{d_u}{d_t}\right) \quad (4\text{-}7)$$

4.6 Force Analysis Model

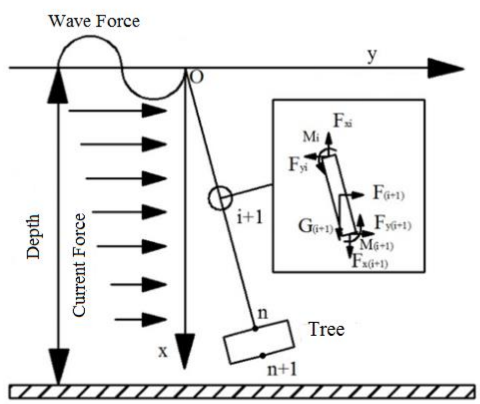

Figure 7 Mechanical Analysis Diagram of Drill Pipe Installation Method

Since the system is influenced by the joint action of waves and currents, the environmental loads F_i on unit i of the riser can be calculated by the following formula:

$$F_i=\frac{\rho_w}{4}C_D Dl_i\left(v_{ci}|v_{ci}|+v_{c(i-1)}\left|v_{c(i-1)}\right|+u_i|u_i|+u_{i-1}|u_{i-1}|\right) \quad (4\text{-}8)$$
$$+\frac{\pi}{8}\rho_w C_M D^2 l_i\left(\frac{du_i}{dt}+\frac{du_{i-1}}{dt}\right)$$

In the formula, $i=1,2,\ldots,n$.

The environmental load of the tree is calculated by the following formula:

$$F_{tree} = \frac{\rho_w}{4} C_{D1} B \left(v_{c(n+1)} \left| v_{c(n+1)} \right| + v_{cn} \left| v_{cn} \right| + u_{n+1} \left| u_{n+1} \right| + u_u \left| u_n \right| \right) \quad (4\text{-}9)$$
$$+ \frac{1}{1} \rho_w C_{M1} V \left(\frac{du_{n+1}}{dt} + \frac{du_n}{dt} \right)$$

In the formula,

C_{D1}——horizontal drag force coefficient of the tree;

B——horizontal drag area of the tree, m^2;

C_{M1}——inertia coefficient of the tree;

V——volume of displacement of the tree, m^3.

As the riser is homogeneous, the dead weight G_i of differential cell i of the riser can be simplified to the center of gravity:

$$G_i = w \bullet l_i \bullet g \quad i = 1, 2, \ldots, n. \quad (4\text{-}10)$$

In the formula, w——wet weight of unit length of the riser, kg.

In the process of laying down, the tree would not be affected by the pressing force. The dynamic effect can be calculated by the dynamic amplification factor (DAF):

$$F_{total} = DAF \bullet F_{sta} \quad (4\text{-}11)$$

$$F_{sta} = m_{tree} \bullet g + m_{other} \bullet g \quad (4\text{-}12)$$

In the formula,

F_{total}——resultant force of system, kN;

F_{sta}——static force, kN;

m_{tree}——mass of the subsea tree in the air, kg;

m_{other}——mass of the laying-down rigging and other accessories, kg.

Acting force F_{yi} on pitch point i of the riser from direction y:

$$F_{yi} = \sum_{i=1}^{n} F_i + F_{tree} \; (i = 1, 2, \ldots, n) \quad (4\text{-}13)$$

Acting force F_{xi} on pitch point i of the riser from direction x:

$F_{xi} = F_{total} + w \bullet (n-i) \bullet l_i \bullet g \qquad (i = 1, 2, \ldots, n)$ （4-14）

The expression of resultant force on pitch point i is:

$T_i = \sqrt{F_{xi}^2 + F_{yi}^2} \quad (i = 1, 2, \ldots, n)$ （4-15）

According to the force analysis, the equilibrium equation of bending moment of differential cell i+1 can be established

$$M_i = \left(F_{y(i+1)} + F_{i+1}/2\right) \cdot l_i + M_{i+1} -$$
$$\left(F_{x(i+1)} + G_{i+1}/2\right) \cdot \left(y_{i+1} - y_i\right)$$

（4-16）

When the riser is divided into much enough, $F(i+1) \leq Fy(i+1)$, $G(i+1) \leq Fx(i+1)$. Therefore, according to the beam bending theory and finite difference method, the equlibrium equation of bending moment can be simplified as:

$$M_i = EI \frac{y_{i+1} - 2y_i + y_{i-1}}{l_i^2} = F_{y(i+1)} \cdot l_i + M_{i+1}$$
$$-F_{x(i+1)} \cdot \left(y_{i+1} - y_i\right)$$
（4-17）

Since the top of the riser is fixed to the tensioner, the top boundary condition can be obtained, that is, the offset y_0 of the laying-down point in the direction y is:

$y_0 = 0$ （4-18）

The end of the riser is connected to the tree by hoist cable, which can be simplified as hinge joint. Thus, the boundary condition of the riser end is:

$F_{xn} = F_{total} \; F_{yn} = F_{tree}$ （4-19）

$M_n = EI \frac{y_{n+1} - 2y_n + y_{n-1}}{l_i^2} = 0 \Rightarrow y_{n+1} = 2y_n - y_{n-1}$ （4-20）

System of linear equations with n unknown can be obtained by combining boundary conditions with the equilibrium equation of bending moment:

$$\frac{EI}{l_i^2} y_{i+2} - \left(\frac{3EI}{l_i^2} + F_{x(i+1)}\right) y_{i+1} + \left(\frac{3EI}{l_i^2} + F_{x(i+1)}\right)$$
$$-\frac{EI}{l_i^2} y_{i-1} = -F_{y(i+1)} l_i \qquad (i = 1, 2, \ldots, n-1)$$
(4-21)
$$-\left(\frac{3EI}{l_i^2} + F_{x(i+1)}\right) y_{i+1} + \left(\frac{2EI}{l_i^2} + F_{x(i+1)}\right) y_i$$
$$-\frac{EI}{l_i^2} y_{i-1} = -F_{y(i+1)} l_i \qquad (i = n)$$

(4-22)

Lateral displacement of each pitch point of the riser is obtained: $y_1, y_2, \ldots, y_n$, and the bending moment of each pitch point is finally obtained.

$$M_i = EI \frac{y_{i+1} - 2y_i + y_{i-1}}{l_i^2} \quad (4\text{-}23)$$

In the formula,

EI ——bending rigidity of riser.

4.7MATLAB Solution and Calculation

When using MATLAB to solve the model, the model parameters are set as follows: wet weight of the tree is 50t, the tree height is 4.7m, volume of displacement of the tree is $15.3m^3$, horizontal drag area is $10m^2$, horizontal drag force coefficient of the tree is 1.6, inertia coefficient of the tree is 2.3; height of the drill pipe is 100m, outer diameter of the drill pipe is 0.127m, wall thickness is 0.0127m; horizontal drag force coefficient of the drill pipe is 1.32, inertia coefficient of the drill pipe is 2, elastic modulus is 2.06×10^5Mpa; water depth is 105m, sea-water density is $1025kg/m^3$, wave height is 1m, wave period is 9s, tidal velocity of the sea surface is 1.02m, sea surface wind speed is 1m/s. It is on this premise that the lateral displacement, bending moment and Mises stress of the riser can be studied, and the final result of MATLAB solution is obtained, shown as figure 8, figure 9 and figure 10.

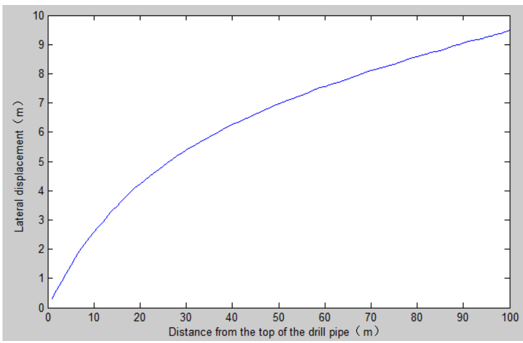

Figure 8 Lateral Displacement Diagram

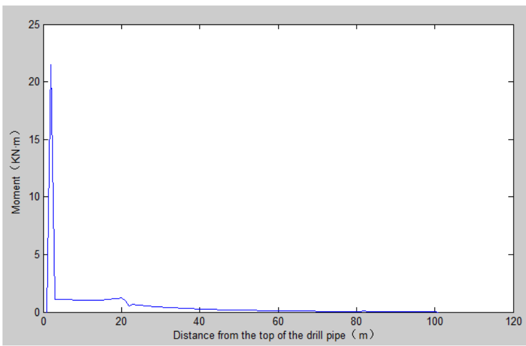

Figure 9 Bending Moment Diagram

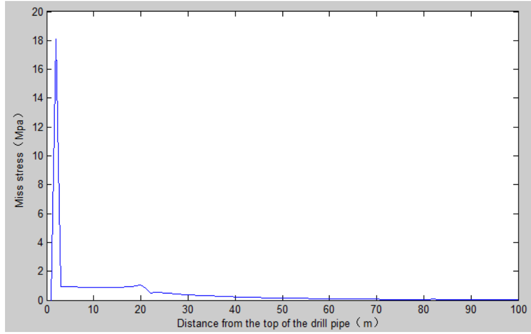

Figure 10 Mises Stress Diagram

It can be seen from the above figures that lateral deformation is the main change on the drill pipe, with a maximum displacement of 9.48m at the bottom of the drilling riser. The increasing rate of the lateral displacement decreases with the increase of water depth. The bending moment is mainly concentrated in the upper part close to the surface of the water, and the maximum value is 21.503KN·m at the top of the drilling riser. The Mises stress is concentrated in the upper part close to the surface of the water, and its maximum sheering force value is 18.11MPa at the top of the drilling riser.

5 Conclusions

Sea experiment is a very important test for subsea tree before put into production. Based on the structure of subsea vertical tree and the assembling characteristics of wellhead, installation testing content, process and method for sea experiment are designed in this paper, and the force condition of drill pipe in the process of laying-down and installation is analyzed according to the installation method and characteristics. The study results can provide reference for the installation exercise of sea experiment of domestic subsea vertical tree and related subsea production equipment.

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