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Lateral bearing characteristics of subsea wellhead assembly in the hydrate trial production engineering

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ABSTRACT

Conductor and suction anchor are the key equipment providing bearing capacity in the field of deep-water drilling or offshore engineering, which have the advantages of high operation efficiency and short construction period. In order to drill a horizontal well in the shallow hydrate reservoir in the deep water, the suction anchor wellhead assembly is employed to undertake the main vertical bearing capacity in the second round of hydrate trial production project, so as to reduce the conductor running depth and heighten the kick-off point position. However, the deformation law of the deep-water suction anchor wellhead assembly under the moving load of the riser is not clear, and it is necessary to understand the lateral bearing characteristics to guide the design of its structural scheme. Based on 3D solid finite element method, the solid finite element model of the suction anchor wellhead assembly is established. In the model, the seabed soil is divided into seven layers, the contact between the wellhead assembly and the soil is simulated, and the vertical load and bending moment are applied to the wellhead node to simulate the riser movement when working in the deep water. The lateral bearing stability of conventional wellhead assembly and suction anchor wellhead assembly under the influence of wellhead load is discussed. The analysis results show that the bending moment is the main factor affecting the lateral deformation of the wellhead string; the anti-bending performance from increasing the outer conductor diameter is better than that from increasing the conductor wall thickness; for the subsea wellhead, the suction anchor obviously improves the lateral bearing capacity and reduces the lateral deformation. The conduct of the suction anchor wellhead assembly still needs to be lowered to a certain depth that below the maximum disturbed depth to ensure the lateral bearing stability，Thus, a method for the minimum conductor running depth for the suction anchor wellhead assembly is developed. The field implementations show that compared with the first round of hydrate trial production project, the conductor running depth is increased by 9.42 m, and there is no risk of wellhead overturning during the trial production. The method for determining the minimum conductor running depth in this paper is feasible and will still play an important role in the subsequent hydrate exploration and development.

1. Introduction

Because of the poor bearing capacity of the highly saturated soil in the deep-sea seabed, the use of conductor or suction anchor to provide a stable and reliable support for the wellhead assembly of deep-water oil and gas wells or subsea production system equipment is the key to ensuring the smooth construction of deep-water oil and gas fields. The conductor is typically a 30 inches (1 inch=2.54 cm) or 36 inches diameter steel pipe. The frictional resistance generated by the contact between the pipe string and the seabed soil is used to support the weight of the upper subsea wellhead and drilling and production equipment, so as to prevent the wellhead assembly from collapsing and being scrapped. The

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suction anchor is a thin-walled cylinder with a closed top and an open bottom, which penetrates into the seabed under the action of its own weight and internal and external pressure difference to become a load-bearing base. Compared with the conductor installation mode, the Suction anchor installation does not need to use the drilling platform with a high daily cost, and has the characteristics of strong bearing capacity, fast installation speed, low construction cost and reusability. For the hydrate reservoir with a burial depth of 200–300 m, the suction anchor can greatly reduce the depth of the conductor, thus improving the position of the deflection point of the horizontal well, which is conducive to the implementation of horizontal well drilling in shallow formations. And the drainage area and the productivity of a single well are increased. In 2019, the suction anchor, as a key bearing foundation, has been successfully used in the second round of natural gas hydrate trial production in China, which has played an extremely important role in improving the productivity of a single well (Ye JL et al., 2020; Li B et al., 2022; Shaibu R et al., 2021; Li YL et al., 2021; Qin XW et al., 2022; Zhu P et al., 2022).

The bearing capacity analysis and safety assessment of deep-water wellhead assembly are the keys in the design of the subsea wellhead. However, at present, the longitudinal bearing capacity and running depth of wellhead are mainly concerned, and the lateral stability analysis is less (Yang J et al., 2003; Tang HX et al., 2011; Liu SJ et al., 2013). Mcclelland B and Focht JA (1956) proposed that the p-y curve method can be used to calculate the actual bearing capacity of pile-soil according to the stress-strain relationship. Wolters JG and Marcon NV (1973) studied the interaction mechanism between wave and offshore structure, pile and platform, pile and soil, as well as the variation law of lateral bearing capacity of offshore platform legs. In 2009, Su KH (2009) established a mechanical analysis model of riser-wellhead-conductor to study the wellhead stability by using the p-y curve of subgrade reaction in soil mechanics. In 2011, Yang J (2011) applied ANSYS software to analyze the lateral bearing capacity of the drilling conductor system in a shallow water block in the Bohai Sea and carried out the simulation analysis. In 2012, Pilisi N et al. (2012) analyzed the strength and stability of the drilling conductor of jacket platform and tension leg platform subjected to hydrodynamic load and pile-soil contact. In 2014, Wang YB (2014) compared and analyzed the contact mechanics method and the contact surface element method to simulate the lateral deformation of the conductor. The lateral displacement of the conductor calculated by the contact surface element method was larger, and it was considered that the contact surface model had a greater impact on the calculation of the lateral load of the string. In 2019, Liu QY et al. (2019) used mechanical equivalent conversion method to deal with the wellhead load, and in their study, ANSYS software was used to analyze the mechanical properties and influencing factors of the conductor pile foundation. The conclusion was that the wellhead lateral load was the main factor affecting the displacement, while the axial load had a negligible effect on the lateral displacement, and the mechanical properties of the foundation had a significant effect on the displacement and stress of the drilling conductor.

As a new type of wellhead assembly, in the aspects of the stress and deformation, the suction anchor wellhead assembly is different from the suction anchor of offshore engineering equipment and the deep-water conductor. Liu JL et al. (2016) considered that the horizontal bearing capacity of deep-water mooring was related to the location of mooring point. The three-dimensional finite element method was used to analyze the horizontal bearing properties of the suction anchor, and the quantitative relationship between the location of mooring point and the horizontal ultimate bearing capacity was discussed. Guo R (2019) found that based on the soil cyclic weakening model, the weakening effect of the side soil of the wellhead suction anchor caused by the cyclic load was more significant than that of the bottom soil, and the lateral bearing capacity of the structure was significantly reduced. For offshore wind turbines, jacket platforms and deep-water oil and gas production facilities, the deformation and failure mechanism of the suction anchor foundation was related to the loading direction. Overall, in the study of the ultimate bearing capacity of the suction anchor, forward rotation failure, translational sliding failure and backward rotation failure are the focuses, but there are differences between the wellhead assembly with suction anchor and the structure of wind turbine and offshore platform. On the other hand, there is not enough attention has been paid on the research of optimizing the design of conductor and surface casing based on suction anchor.

The suction anchor has been successfully employed in the second round of hydrate trial production project because of its high vertical bearing capacity. However, how to determine the conductor running depth and heighten the kick-off point position for the horizontal well as far as possible in the structural design of the suction anchor wellhead assembly has become one of the key issues affecting the structural design. Because the constraint mode of the conductor of the deep-water suction anchor wellhead assembly is different from that of the general wellhead assembly, the deformation law of the conductor under the moving load of the riser is not clear. In order to further understand the lateral deformation of wellhead assembly, and deeply analyze the mechanical property of wellhead loading capacity, in this paper, on the basis of the three-dimensional solid simulation analysis method, the longitudinal or lateral bending moment load imposed on the wellhead assembly during the riser movement or drilling and completion operations is simplified, the finite element analysis model is established for the pile-soil contact effect of suction anchor-wellhead-conductor-shallow soil, the lateral bearing properties of the wellhead suction anchor and general wellhead are compared, and the influence of wellhead load, mud height, wall thickness combination and other factors on the lateral bearing capacity of conductor is analyzed through an example. The research results have guiding values for the design of suction anchor and the installation of deepwater conductor.

2. Subsea wellhead assembly

2.1. Conventional wellhead assembly

The deep-water wellhead assembly is composed of wellhead housing, high-pressure wellhead and external conductor + surface casing, as shown in Fig. 1a. The wellhead housing and conductor are usually installed on the seabed by jetting. Then, the seabed is continuously drilled to form a new borehole, and the high pressure wellhead and surface casing are run into the new borehole to connect with the wellhead housing.

2.2. Suction anchor wellhead assembly

The suction anchor wellhead assembly adds a set of suction anchors as the main source of longitudinal bearing capacity on the basis of the conventional deep-water wellhead assembly, as shown in Fig. 1b. Suction anchors rely on the longitudinal friction between the anchor body and the surrounding soil, and the support reaction force between the top plate of the suction anchor and the soil inside the anchor to provide longitudinal bearing capacity. During installation progress, the suction anchor is firstly inserted into the mud on the seabed by means of self gravity. And the seawater in the cylinder is discharged through the top suction pump to form a negative pressure. So, when the differential pressure acting force of the anchor top is greater than the frictional resistance of the anchor body and the soil body, the anchor body is continuously pressed into the soil body until sinking to a design position.

Compared with the first round of natural gas hydrate trial production project, the second round of natural gas hydrate trial production project first installed suction anchors on the seabed (Fig. 2), thus providing 350−700 tons of vertical support force for wellhead assembly and blowout preventers, effectively avoiding wellhead subsidence. On the basis of sufficient bearing capacity of the suction anchor, the reduction of the running depth of the conductor and the enhancement of the deflection point height and the maximum deflection rate of the horizontal well will provide more selection space for drilling engineering design.

2.3. Wellhead lateral stability analysis method

Deep-water wellhead assembly mainly bears the gravity of subsea blowout preventer, the lateral bending moment caused by riser movement, foundation reaction, the weight of multi-layer casing suspended inside, or the additional temperature and pressure loads caused by operation conditions during drilling and completion operations. The harsh stress environment and complex wellhead structure make it very critical to carry out the stress analysis of wellhead assembly.

The calculation and analysis methods of the lateral bearing of the conductor are mainly divided into three categories. One is to use the continuous beam model combined with the foundation reaction method, in which the pile-soil contact between the conductor and the soil body is simplified as a linear spring or a nonlinear spring, and a mechanical equation of the conductor model is established to solve problems according to the continuous conditions of bending moment, displacement and shear force at the node. Thus, the stress deformation data of the conduct system under the wellhead load are obtained (Deng S et al., 2019; Guan ZC et al., 2009). The second is to establish a finite element model of the deep-water subsea wellhead assembly and soil body three-dimensional entity, in which the soil counterforce is simulated by adopting surface-to-surface contact between the soil body and the wellhead assembly, and the finite element

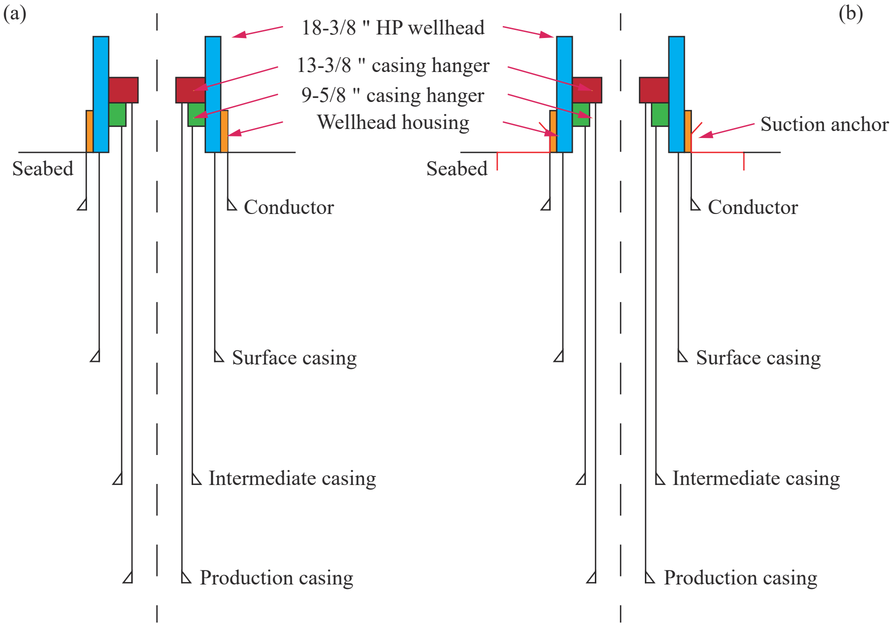

Fig. 1. Schematic diagram of conventional deep-water wellhead assembly (a) and deep-water wellhead assembly with suction anchor (b).

analysis model is established to solve problems. Thus, the bending moment, the displacement and other data of the conductor or the wellhead section are extracted in the finite element model database (Liu QY et al., 2019). And the third is to establish a three-dimensional solid finite element or beam element model of the deep-water wellhead assembly, in which the foundation reaction between the conductor node and the soil is treated as the action of a nonlinear spring action, and the conductor node is displaced under the action of the P-Y curve. Thus, the displacement, the rotation angle and other data of the conductor node are obtained by solving the finite element model (Chang YJ et al., 2019).

3. Wellhead stress analysis model

3.1. Assumptions

(a) The material of the conductor and suction anchor is isotropic, homogeneous and linear elastic steel, and the local influence of the conductor joint is ignored.

(b) The connection mode among the high pressure wellhead, wellhead housing and suction anchor is simplified as binding constraint, and the influence of micro-structure is ignore.

(c) The initial mechanical properties of the seabed soil have been restored by ignoring the disturbance of the suction anchor installation and the conductor jet on the shallow surface.

(d) All model loads are imposed on the coupling point at the upper end of the wellhead.

(e) Documents used for mechanical parameters of soil layer (Wang YB et al., 2014) as shown in Table 1.

Fig. 2. Suction anchor of second natural gas hydrate trial production.

3.2. Finite element analysis model

Considering the influence of soil boundary on the stress and deformation of the string, and the soil disturbance radius is greater than 40 times of the string diameter, the length and width of the model soil body are set to be 40 m × 20 m, and the distance between the bottom boundary of the soil body and the conductor is 30 m. the C3D8R unit is used for the conductor and suction anchor, and the Mohr-Coulomb model is used for describing the contact action of seabed soil and pile-soil. In order to simplify the numerical calculation, a half geometric model is taken to establish the wellhead-suction anchor-soil body three-dimensional finite element analysis model. The wellhead-suction anchor-soil body model is shown in Fig. 3.

3.3. Boundary conditions

Boundary conditions are set for wellhead, soil body and suction anchor respectively, wherein the bottom of the soil body limits the degree of freedom in the x, y and z directions;

Table 1. Soil mechanical parameter.

Materials	Elasticity modulus/ MPa	Internal friction angle/°	Cohesive force/kPa	Poisson's ratio	Thickness /m
Soil layer 1	2	5	5	0.4	21
Soil layer 2	2	20	20	0.4	9
Soil layer 3	10	30	45	0.4	8
Soil layer 4	10	30	50	0.4	7
Soil layer 5	10	35	100	0.4	12
Soil layer 6	10	30	150	0.4	22
Soil layer 7	10	35	150	0.4	23

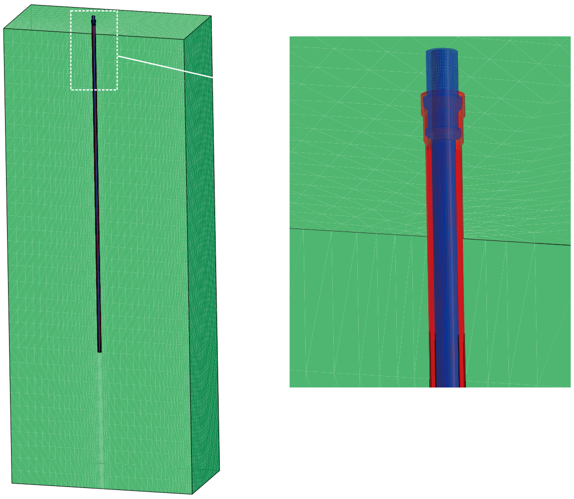

Fig. 3. FEA simulation analysis model of wellhead-soil body.

the symmetrical plane of the wellhead, the soil body and the suction anchor limits the displacement in the y direction; the soil body perimeter limits the degree of freedom in the X and y directions. To reduce the non-linear effects of irregular geometry and complex contacts at the wellhead assembly, the binding constraint is adopted among the high-pressure wellhead, low-pressure wellhead and suction anchor.

3.4. Model parameter

Dimensional parameters of the conductor and surface casing are as follows in Table 2. Material differences of the conductor, surface casing, wellhead and suction anchor are ignored. According to the soil parameters of the South China Sea shallow formation, the soil body is divided into 7 layers, and the detailed material parameters are shown in Table 3.

4. Mechanical analysis of wellhead assembly

4.1. Wellhead load

Bending moment and vertical load are applied at the wellhead according to the characteristics of the load applied at the wellhead, the simulation results are shown in Fig. 4. The effects of bending moment and lateral load on the bending moment and lateral displacement of the pipe body are as follows in Fig. 5, the wellhead deflects along the direction of bending moment application, thus resulting in lateral displacement and separation of the conductor from the soil body. the comparative analysis data of Fig. 5a indicates that the wellhead bending moment increases while the string bending moment and lateral deformation decrease with the increase of string depth when the vertical load is kept constant. The lateral displacement of the string and the change of the section bending moment are concentrated in the upper part of the conductor. As can be seen in Fig. 5b, the reason why the bending moment of the second node of the string changes greatly is that there is no external horizontal counterforce support for the conductor in the seawater section, and there is no cement sheath inside. The conductor at this node is unconstrained free deformation, so the bending moment of the conductor section is small. By keeping the wellhead bending moment unchanged and increasing the vertical load from 200 tons to 400 tons (Fig. 5c and Fig. 5d), the lateral displacement and bending moment of the string are basically unchanged, which indicates that the vertical load has a small effect on the lateral displacement of the string. Therefore, it is one of the key steps in the design of conductor string to carry out the stress deformation of the shallow formation string. For the deep-water operation area with complex sea conditions, the bending resistance of the shallow conductor should be strengthened, which is the premise to ensure the drilling and completion of deep-water oil and gas wells.

Table 2. Size parameter of conductors and surface casing.

Component parts	Diameter/cm	Thickness/cm	Length/m
Conductor 1	91.44	3.81	25
Conductor 2	91.44	2.54	48
surface casing	50.80	1.27	70

Table 3. Material parameter of FEM model.

Parts	Elasticity modulus /MPa	Poison’s ratio
Conductor/surface casing/wellhead/ suction anchor	2.1×10^6	0.25
cement	2×10^5	0.35

4.2. Diameter and wall thickness combination of conductor

4 combinations of the conductor diameter and wall thickness are set up, as shown in Table 4. The effect of the combination of conduct wall thickness and running depth on

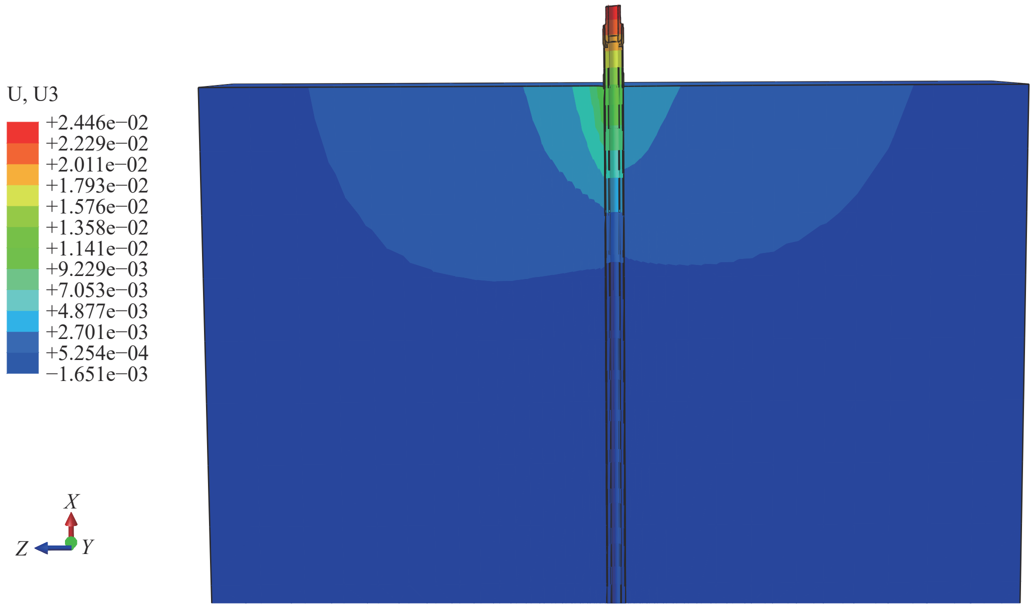

Fig. 4. Simulation analysis results of lateral bending deformation of wellhead assembly.

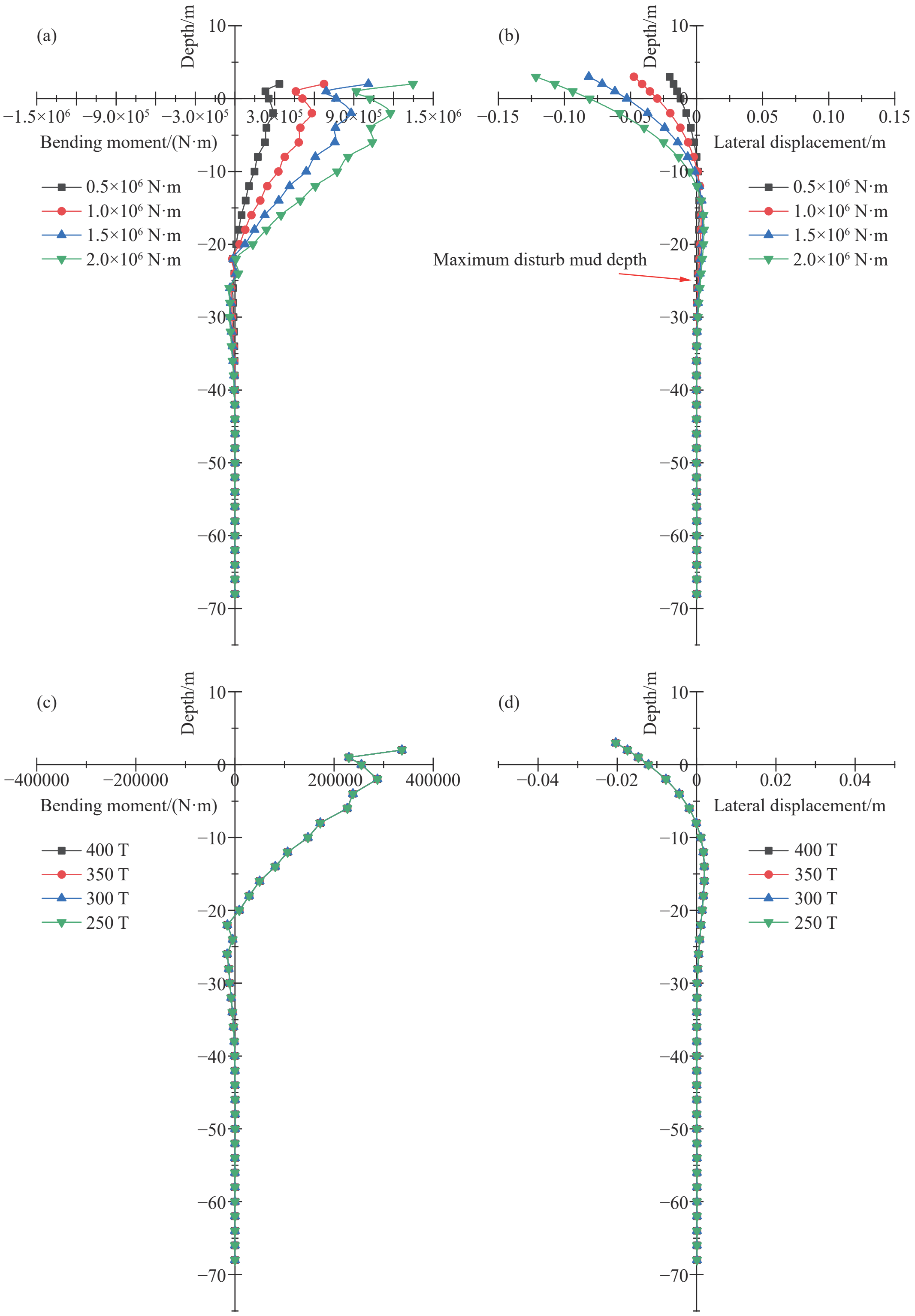

Fig. 5. (a)–Effect of wellhead bending moment on conductor bending moment distribution; (b)–Effect of wellhead bending moment on lateral deformation of conductor; (c)–Effect of vertical wellhead load on conductor bending moment distribution; (d)–Effect of wellhead vertical load on lateral deformation of conductor.

Table 4. Parameters of conductor combinations.

Combination	Diameter/ cm	Thickness/ cm	Length/ m	Total length of conductor/m
A1	91.44	3.81	25	73
A2	91.44	2.54	25	73
A3	76.20	3.81	25	73
A4	76.20	2.54	25	73

the lateral displacement and bending moment is shown in Fig. 6a. When the wellhead bending moment of 1×10^6 N·m is kept unchanged, and the wall thickness of the conduit is reduced from 3.81 cm to 2.54 cm, the bending moment difference of the string body is small. As shown in Fig. 6b, the lateral deformation of the conductor increases when the wall thickness of the conductor decreases. When the riser

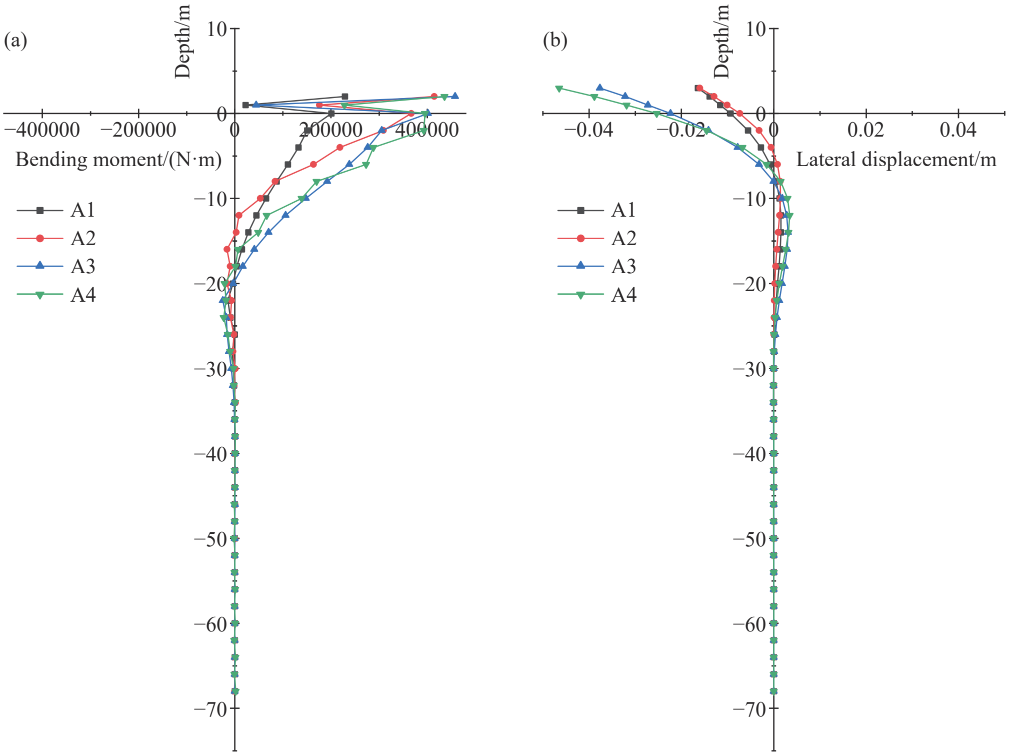

Fig. 6. (a)–Effect of string structure combination on bending moment distribution of conductor; (b)–Effect of string structure combination on lateral deformation of conductor.

outer diameter is reduced, the lateral deformation of the conductor increases significantly. Increasing the outer diameter of the conductor has a better effect on improving the anti-bending stiffness of the conductor than increasing the wall thickness, and it is more obvious to reduce the lateral deformation of the conductor. Therefore, the conductor with outer diameter of 91.44 cm is preferred in deep-water wellbores.

4.3. Running depth of conductor with wall thickness 3.81 cm

The effect of the running depth of the conductor section with a wall thickness of 3.81 cm on the string is as follows in Fig. 7, As can be seen from Fig. 7a, the longer the running depth of the 3.81-cm-thick conductor at the wellhead is, the greater the bending moment of the conductor at the shallow part is, but the overall difference is small. As shown in Fig. 7b, the deeper the running depth is, the smaller the wellhead deformation is, which indicates that increasing the wall thickness of the conductor in the shallow formation can effectively reduce the lateral deformation of the wellhead, especially in shallow soft formation, the greater the running depth of the conductor with a large wall thickness is, the safer the wellhead is under complex sea conditions.

5. Stress deformation analysis of suction anchor wellhead assembly

5.1. Lateral bearing capacity of suction anchor

The stress deformation diagram of suction anchor wellhead assembly is shown in Fig. 8. The suction anchor is slightly deflected along the bending moment loading direction on the basis of the lateral action caused by the riser movement, the left side of the suction anchor is separated from the formation, the right seabed surface is deformed by the extrusion of the suction anchor, and the left soil area inside the suction anchor is greatly affected.

It can be seen from Fig. 9 that the maximum wellhead displacement increases with the increase of the wellhead bending moment. The bending moment changes greatly at 1 m above the seabed. The bending moment changes from negative to positive, and then to negative at the seabed. The bending moment of the conductor is laterally constrained by the supporting ring of the central pipe of the suction anchor. The shear force direction of the conductor above and below the supporting ring is different, so the bending moment direction changes at the connection between the suction anchor and conductor. The maximum lateral deformation position of the string below the mudline is −15 m, and with the increase of the bending moment, the lateral deformation of the string at the buried depth of 15 m increases. The central tube of suction anchor has no supporting effect on the conductor, and the soil layer below the central tube has a lateral restraint deformation effect on the conductor.

5.2. Comparison between wellhead devices with suction anchor and conventional wellhead devices.

The comparison results of bending moment and lateral deformation between suction anchor wellhead device and conventional wellhead device are shown in Fig. 10. the bending moment fluctuation of the suction anchor wellhead

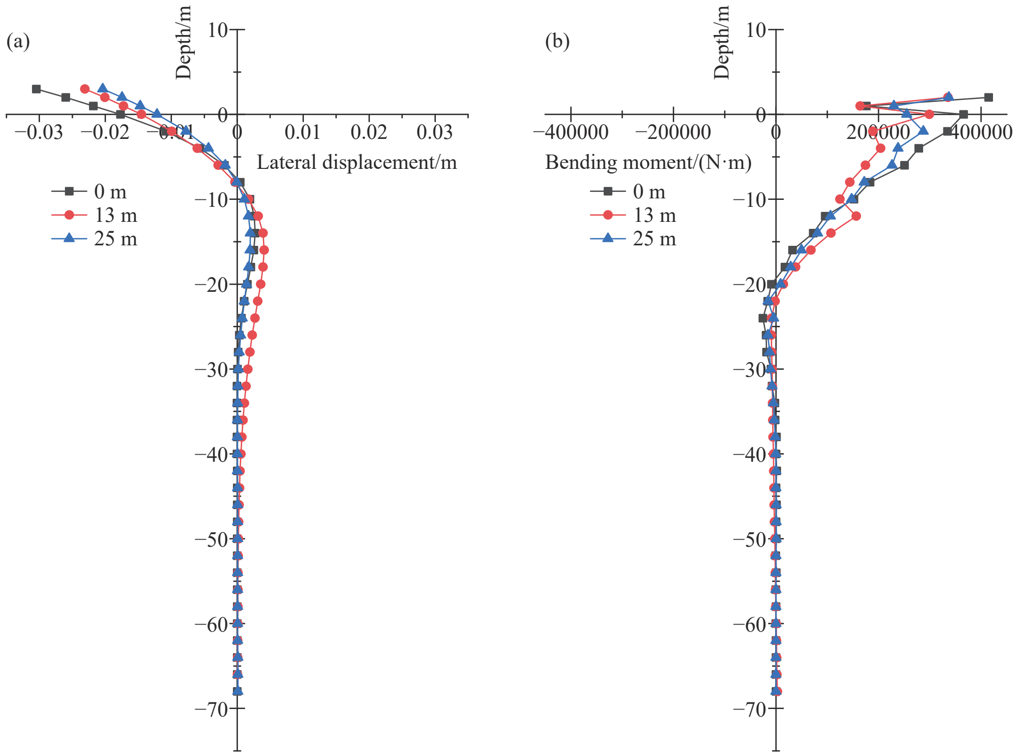

Fig. 7. (a)–Effect of running depth of 3.81 cm conductor section on bending moment distribution; (b)–Effect of running depth of 3.81 cm conductor section on lateral deformation.

devices at 1 m above the seabed is great than that of conventional wellhead device due to suction anchor deflection shared a portion of bending moment. Therefore, the bending moment distribution of conductor below the seabed with suction anchor is significantly lower than that of conventional wellhead device, and the bending moment trend below the mudline is basically the same at the 15 m.

In terms of lateral deformation, under the conditions of the same bending moment and vertical load, the suction anchor reduces the lateral displacement at the top of the conductor, but the depth of the zero displacement point and the maximum lateral displacement below it are higher than those of the conventional wellhead assembly because there is no constraint support in the central tube. the maximum disturbed mud depth of the conventional wellhead is −30 m, while the maximum disturbed mud depth of the suction anchor wellhead is −55 m. If the running depth of the conductor is more than −55m, the lateral constraint at the bottom of the conductor is poor and the overall deflection occurs. Therefore, on the premise that the bearing capacity of the suction anchor wellhead assembly meets the design requirements, in order to avoid the wellhead deflection caused by too large overall deflection angle of the conductor, it is recommended that the running depth of the conductor of the suction anchor wellhead assembly should exceed −55m.

6. Field implementation of suction anchor wellhead assembly

In the second round of natural gas hydrate trial production, the suction anchor was placed on the seabed by an engineering vessel. Then, the wellhead housing and conductor are connected on the “BLUEWHALE II” drill platform. In order to prevent the unfavorable influence of sea conditions and platform movements, drilling rig opened the heave compensation after the conductor shoe reached the suction anchor, and then the conductor was jet to the depth of 61.8 m below the mudline. However, in the first round of the natural gas trial production, the conductor jetting depth was 71.22 m (Li WL et al., 2019). A remotely operated vehicle (ROV) confirmed that the final installation inclination of underwater wellhead bovine eye reading is 0.5°, which meets the accuracy requirement of bovine eye reading <1°, and the subsequent drilling and completion can be carried out. Because the suction anchor placed in advance has an enough bearing capacity, the conductor is not suspended at the wellhead to wait for the recovery of soil bearing capacity after the conductor jetting is completed, which saves about one day of rig time. During the test period of the second hydrate trail production project, the suction anchor wellhead assembly did not have wellhead overturning, settlement and other problems during the trial production period. There was no interface separation between the suction anchor wellhead assembly and the surrounding soil, which had a good lateral restraint effect and successfully guaranteed the smooth implementation of the trial production project.

7. Conclusions

The conclusions of this study are as follows:

(i) Compared with the traditional bending rigidity enhancement methods such as increasing the diameter or wall thickness of the conductor, suction anchor has been proven to be a more effective method in terms of the enhancement performance. Under the same load condition, the lateral displacement decreases from 2.04 cm to 1.20 cm. Through pile-soil contact action, the suction anchor exerts lateral constraint on conductor at mudline, which reduces the lateral displacement of wellhead and the lateral load component. Compared to the conventional conductor, suction anchor has an advantage on reducing overturning risk of wellhead and ensure wellhead stability.

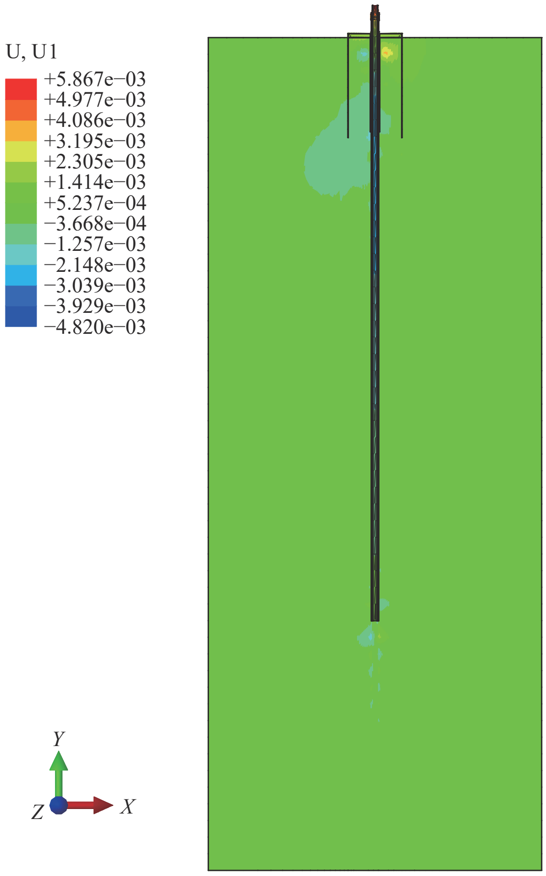

Fig. 8. Lateral deformation simulation results of wellhead device with suction anchor.

(ii) The suction anchor wellhead assembly has a great influence on the stress deformation law of the conductor, and the design of the suction anchor wellhead assembly needs to ensure that the length of the conductor is greater than the maximum depth of mud disturbance in order to obtain a sufficient lateral support, which solves the problem of determining the conductor running depth in the composite bearing design of the suction anchor wellhead assembly.

(iii) The installation of the suction anchor wellhead assembly can give full play to the flexibility of the engineering vessel and the strong operation capability of the drilling platform. The field implementations show that the suction anchor wellhead assembly has significant advantages in saving drilling rig time, heightening the position of the kick-off point and ensuring the verticality of the wellhead, and has a high practical values in improving the efficiency of deep-water hydrate well construction.

CRediT authorship contribution statement

Zeng Jing, Xie Wenwei and Kou Beibei conceived of the presented idea, Lu Jingan and Cai Dejun verified the analytical methods. Li Xingchen and Zhang Kewei polished

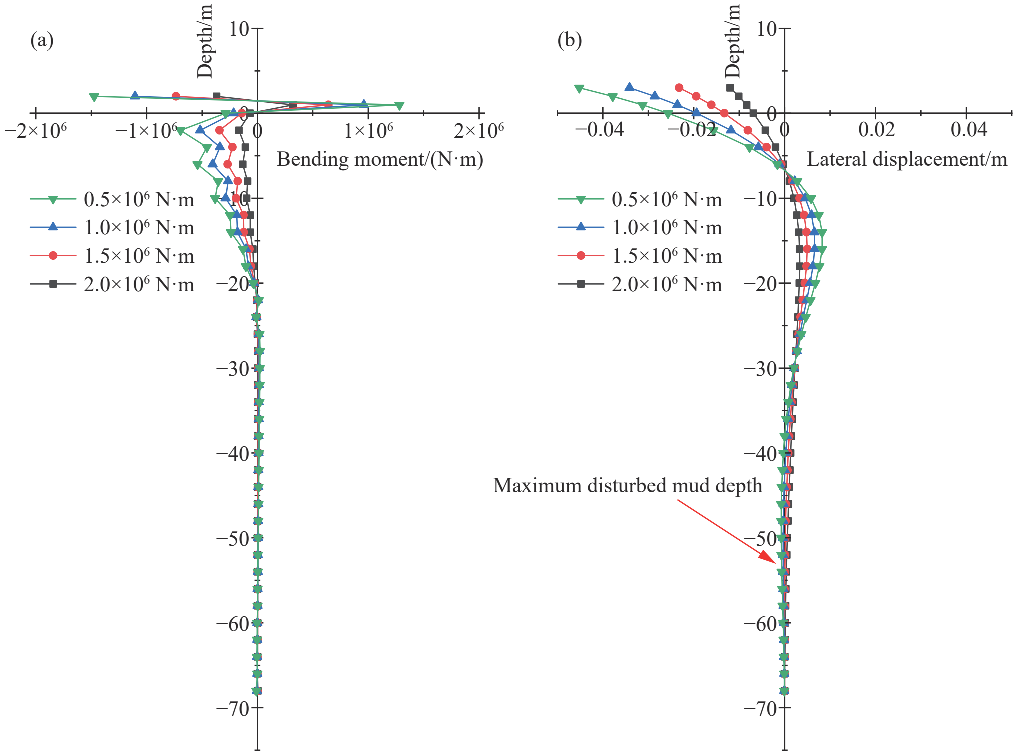

Fig. 9. (a)–Effect of bending moment on bending moment of suction anchor wellhead assembly; (b)–Effect of bending moment on deformation of suction anchor wellhead assembly .

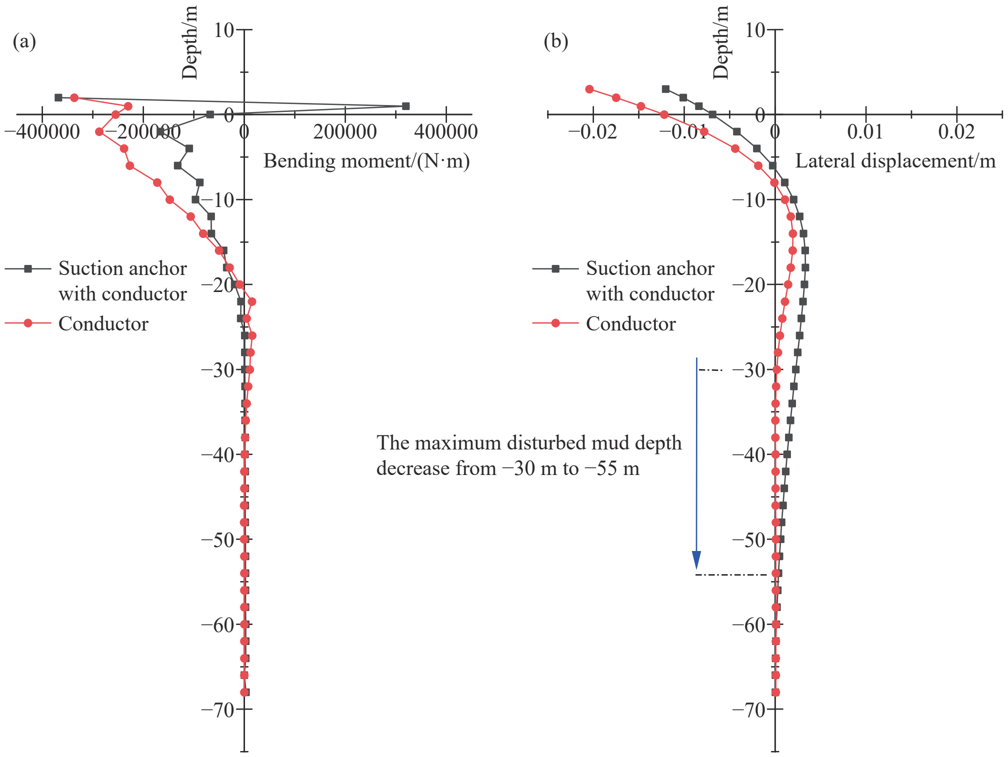

Fig. 10. Comparison of bending moment of wellhead assembly .

up the manuscript. Zeng Jing, Liu Qinghua, Shi Haoxian and Li Jing performed the numerical simulations. Zeng Jing and Li Bo took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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