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FEM analysis of deepwater drilling risers under the operability and hang-off working conditions

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Abstract: In recent years, numerous exploration activities of oil and gas industry have been conducted in ultra deep water. The global offshore industry is building systems today for drilling in even deeper water, progressively using new technologies, and significantly extending existing technologies. This is the general trend in the offshore oil and gas industry. So the technology of ultra-deepwater risers, which is the main tool in drilling oil, is more and more standard. This paper manly focuses on the global analysis of the drilling risers. And it is divided into two parts, operability analysis and hang-off analysis that are used to check the design of the riser. In this paper, the rotation angle and stress of the riser in the drilling mode are calculated to determine the operability envelop. The number of the buoyancy modules has been determined and according to the API standard, all the worked out values have been checked out. From all the above, it is concluded that the operability envelop is relatively small under harsh condition and the number of the buoyancy modules is a little large. And above all, the design of this riser is successful.
Keywords: drilling riser; operability; hang-off; FEM analysis
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1 Introduction

The analysis of riser mechanics can be divided into static analysis and dynamic analysis[1]. The effect of current and the offset of floater is taken into account in the static analysis stage, which is the first step of riser's global analysis, and also the starting point of the following eigenvalue and dynamic analysis. While the dynamic analysis can study the non-liner dynamic responses of the riser, and all the responses are usually activated by the motion of the floater and various dynamic environmental conditions, such as wind, wave and current.

The static and dynamic analysis of the drilling riser in service, as well as the safety of the riser under various environmental conditions, are conducted by using the FEA software ABQUS in this paper. Under harsh environmental condition, the riser should be suspended at the LMRP or BOP, which is defined as a hang-off condition, to ensure that the ocean surface and subsea equipments are not destroyed[2]. The hang-off condition can be classified into two kinds, hard hang-off and soft hang-off, the difference between them is whether the telescopic joint is wiped off. When it is under hard hang-off condition, there is no telescopic joint, the heave motion of the floater will be directly passed on to the riser. While, when it is under soft hang-off condition, the telescopic joint can offset the motion the floater passed to the riser, but the stroke of the TJ is very important now, since it falls in an allowable range. Under extreme sea condition, it is difficult to meet the need of stroke, so the hard hang-off system is selected here[3].

The FEA process of the hang-off riser is similar to the operational riser, which is commonly divided as static analysis and dynamic analysis. But it needs to modify the riser model under these two conditions, and the standards of calibration are different.

2 Brief introduction to the drilling riser

Drilling riser is a special kind of riser, and its design is very important for the process of deepwater drilling. In recent years, there have been many accidents caused by the riser damage. It is an urgent problem that needs design and analysis of the drilling riser.

Risers are from the seabed BOP group to the drilling platform and connected with the control exports of cement. When the drilling platform moves horizontally relative to the seabed wellhead, in order to eliminate bending of the riser, we'll generally install the upper ball joints or flexible joints in the bottom of the riser and BOP

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Group. And as the water depth increases, in order to reduce the drilling platform's motion against the tube bending, a hinge or flexible joints will be installed between the top of the riser and drilling platform, which can bend arbitrarily as much as 10 degrees in the vertical direction. It can effectively reduce the deflection of the riser. In order to eliminate the impact of the vertical movement of the drilling platform against the riser, a telescopic joint is installed in the upper riser. The telescopic joint is composed of inner barrel and outer barrel. The inner barrel is connected with a ball joint or flexible joint, and the outer barrel is connected with a riser joint below to the platform by a number of tensioners.

The drilling riser bears a wide range of loads, including wind force, wave force, tide, weights of the mud and pipes, buoyancy, tension of the tensioner, as well as the force induced by pressure difference between internal mud and external water. The external force acts on the riser in various forms with the deepening of water depth so that the forces are very complex.

In addition, during the deep-sea drilling operations, as the water depth increases, the gravity of riser is gradually increasing. In order to keep the riser vertical, the tension of the tensioner also increases within a limited range. Therefore, in order to reduce the tension, external buoyancy modules are installed on the risers[4]. However, the existence of buoyancy modules would increase the tide and wave forces acting on the risers, and easily damage the foam, so it also uses air-can to adjust the buoyancy of the riser. In addition, the layout of buoyancy modules is not arbitrary, the number of buoyancy modules is to ensure that the tensioner will not be pulled off, and there will be no buckling of the riser.

Besides, for deep-sea drilling riser, a problem that cannot be ignored is what should be done when the drilling platform encounters the storm. If the water is very deep, it is impossible that all the risers can be retrieved, it is often disconnected from the bottom of the riser, so that the riser can hang off to the drilling platform. Since the governing of the riser is more difficult due to bad sea conditions, and in the light of the research, when water depth is more than 2000 feet, the cycle of vibration of the riser is similar to wave cycle. So how to hang off the riser to the platform safely under bad sea conditions is an important aspect to be considered in the design and analysis process.

3 Riser motion equations

The basic assumptions of riser analysis are as follows[5]:

1) In the riser mechanical analysis process, assuming that the material of pipeline is homogeneous and isotropic, and it remains in the linear elastic range in the process of movement and deformation.

2) The movement speed and rotation speed of mud in the riser are small. As a result, the centrifugal force acted on the viscous mud, the reaction force acted on the riser and the Coriolis force acted on riser can be ignored.

3) The impact of bending rigidity of drill pipe against the riser is not considered.

4) Due to that the ratio of length to diameter is very small, risers can be used as flexible beams for the mechanical analysis.

5) Assume that both the deformation of beam and the deformation angle are small.

6) Provided that the direction of current and deformation of riser are in the same vertical plane *XOZ*, and *OX*-axis and the direction of flow in the same direction.

In this assumption, the equation of the horizontal movement is

$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left(EI\frac{\mathrm{d}^2 x}{\mathrm{d}z^2}\right)-\frac{\mathrm{d}}{\mathrm{d}z}\left[\left(T+A_0P_0-A_iP_i\right)\frac{\mathrm{d}x}{\mathrm{d}z}\right]+m_x\ddot{x}=f_{xs}\ , \quad (1)$$

where

$$T_e(z)=T(z)+A_0(z)P_0(z)-A_iP_i(z)\ . \quad (2)$$

4 Numerical solutions

There are many numerical solutions to the static and dynamic equations of risers, such as lumped mass method, finite difference method and finite element method. The finite element method is used commonly.

Some assumption regarding the distribution of the displacement inside the elements has to be made to express the displacements, strain and stress of elements using the displacements of nodes. This is a displacement mode or function.

This function is expressed as follows:

$$\boldsymbol{\delta}=\sum_{i=1}^{n}N_i\boldsymbol{\delta}_i\ . \quad (3)$$

The strain matrix is obtained by calculating the shape functions in the Cartesian coordinate system and putting them in the proper position in the matrix. Elasticity matrix $\boldsymbol{D}$ shows the relation of stress and strain inside elements:

$$\boldsymbol{\sigma}=\boldsymbol{D\varepsilon}\ . \quad (4)$$

Because the riser has a large deformation problem, the tangential stiffness matrix of three-dimensional elements has to be determined before the analysis. Geometry stiffness matrix is:

$$\boldsymbol{k}_\sigma = \int \boldsymbol{G}^{\mathrm{T}} \boldsymbol{M} \boldsymbol{G} \mathrm{d}v \,. \quad (5)$$

Equivalent node forces are obtained by moving the distributed forces to the nodes by the principle of the equal virtual power:

$$\boldsymbol{F}_e = \int \boldsymbol{N}^{\mathrm{T}} \boldsymbol{q} \mathrm{d}v \,, \quad (6)$$

where, $\boldsymbol{N}$ is a shape function matrix and $\boldsymbol{q}$ is a distributed force matrix.

Node forces, node displacements and elements stiffness matrix in the global coordinates can be obtained by the transition matrix. Then the global stiffness matrix can be determined by the principle of superposition. Finally the structural equivalence equation is

$$\boldsymbol{K}\boldsymbol{\delta} = \boldsymbol{F} \,, \quad (7)$$

where $\boldsymbol{\delta}$ is a displacement matrix of the whole structure; $\boldsymbol{F}$ is a force matrix of the nodes; $\boldsymbol{K}$ is a global stiffness matrix. With the given constraint conditions of nodes' forces and displacements, the nodes' displacements and the elements' stresses can be obtained from the equation and other results. However, the dynamic analysis of the riser not only needs the conditions of static analysis, but also the initial conditions.

The finite element method of dynamic analysis is similar to that of static analysis. After discretizing, the standard format of Eq.(1) is

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}\boldsymbol{x} = \boldsymbol{F} \,, \quad (8)$$

where $\boldsymbol{M}$ is a mass matrix of the system (including additional mass); $\boldsymbol{C}$ is a damping matrix (including structural damping and the hydrodynamics damping); $\boldsymbol{K}$ is a global stiffness matrix; $\boldsymbol{x}$, $\dot{\boldsymbol{x}}$ and $\ddot{\boldsymbol{x}}$ are the displacement, velocity and acceleration vector of the nodes, respectively; $\boldsymbol{F}$ is a load vector. When the displacements of the riser's nodes have been obtained, the bending moments and shearing forces can be found by using interpolating function method or difference method.

5 Finite element model

The top of the riser connects to the floater by several tensioners under the operability conditions (drilling conditions), on the other hand, the bottom of the riser interacts with soil, and the furthest bottom is considered fixed. The model excludes the drilling pipe. This can be considered conservative because the drill pipe contributes to the bending and axial stiffness.

Proper element type should be used to describe the mechanical characteristics for the nonlinear riser. There is a type of Hybrid beam elements in the ABAQUS elements library which can be used to model very slender structures. These structures' axial stiffness is greater than their bending stiffness.

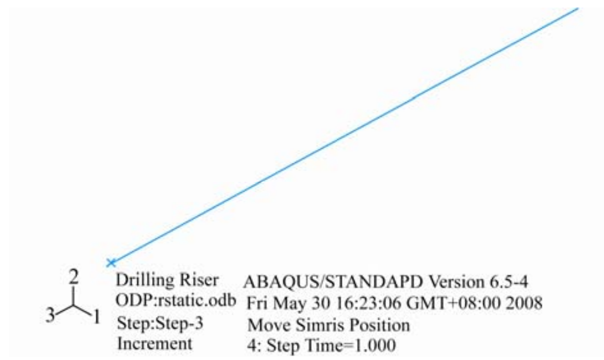

Fig.1 Riser's finite element model of operability

This paper had considered the effects of the three-dimensional loads, so element B31H is chosen. The riser is 3 073.6 m (10 084 ft), divided into 510 nodes and 509 elements. Six additional nonlinear springs are used to model the tensioners and 59 springs are also used to model the interaction between the casing and soil.

The finite element model of the riser is shown in Fig.1. Once the hard hang-off mode is used, the telescopic joint will be removed and the bottom of the riser be disconnected at the LMRP. B31H is also chosen to model riser. The whole model is divided into 435 nodes and 434 elements. A spring whose stiffness is very large is used to connect the riser to the floater. The riser-soil interactions do not need to be modeled because the riser is disconnected at LMRP.

Static analysis is divided into three steps. First, initialize the model and pre-tension. The tensioners are not added into the model. Gravity is loaded. Second, initialize tensioners and remove the pre-tension, and apply current using the AQUA module. The displacement of the floater is zero (neutral position). Third, the displacement of floater is used as the boundary conditions. This is called offset position.

Dynamic analysis, which is a restart analysis, was conducted on the basis of static analysis. So the forth step is moving the floater to a position suitable for the floater's motion. The motion of floater is applied at the fifth step. The motion is applied using ABAQUS's subroutine: DISP.

Hang-off analysis is similar to the operability analysis, which will not be further discussed here.

5.1 Operability results analysis

5.1.1 Distribution of effective tension and bending moment

Figs.2~4 show the effective tension and bending moment under different conditions. It presents that the effective tension of risers reduces from up to down in the static analysis result. The trend of the bending moment corresponds to the actual condition. There is a large value around the tensioner ring, and maximum at the bottom of riser. That's because the bending load of deepwater risers is usually larger at 20~30 m water depth, and also the failure of the existing risers appears at the position of 2-3 risers under water. It presents that these positions are dangerous and the strength of risers should be considered seriously. Since there are flex joint, LMRP and BOP, it can withstand high bending moment for the bottom, and so does in the local analysis. The bottom of riser should be able to resist the bending moment.

Adding an appropriate excursion at the top of risers may affect the effective tension and bending moment. Due to the interaction of the bottom of risers and soil, the three kinds of current considered in this paper have little effect on the effective tension and bending moment of static risers.

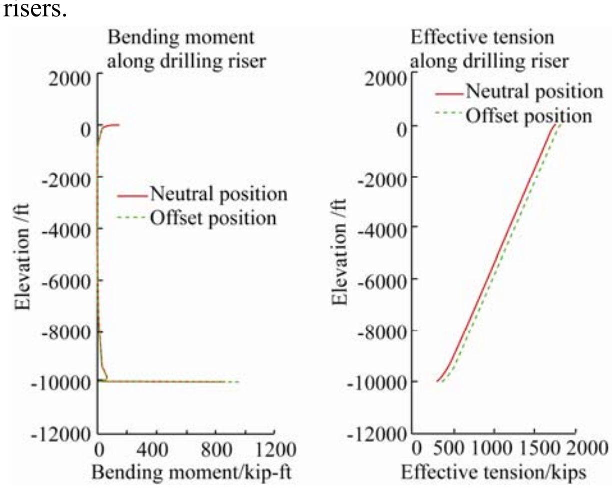

Fig.2 100-year Eddy+1year Bottom

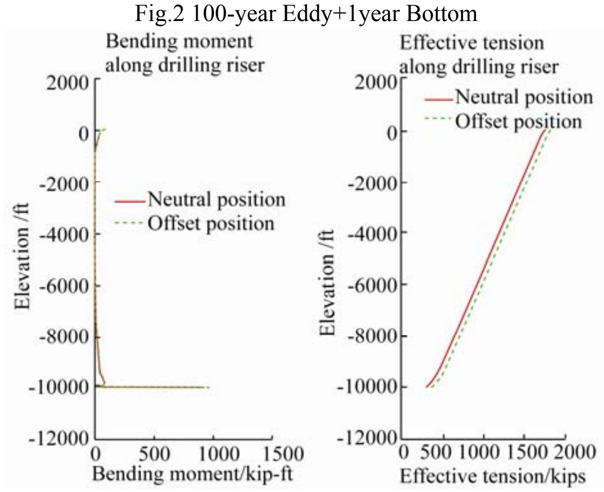

Fig.3 10-year Eddy+1year Bottom

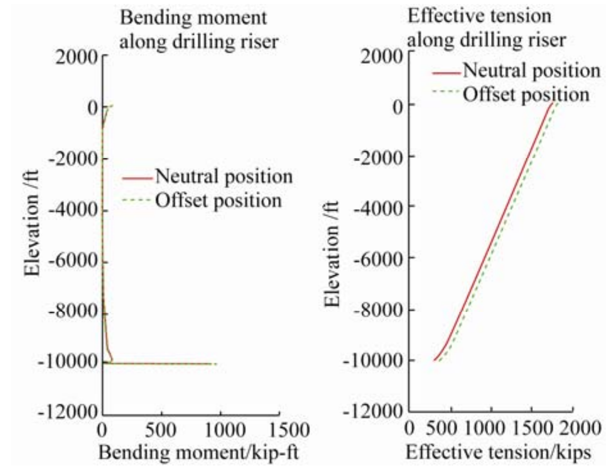

Fig.4 1-year Eddy+1year Bottom

5.1.2 Rotation angles of flex joint

The result of Table 1 shows that, for the rotation angle of the upper flex joint, comparing the result with the criteria, it is found that neither the average angle nor the maximum rotation angle of the 1st current meets the requirement; the average angle of the 2nd current does not meet the requirement either, but the maximum value does; and both the average and maximum rotation angles of the 3rd current meet the requirement defined by the criteria.

For the rotation angles of the bottom flex joint, the result of the three kinds of current presents that the average and maximum values are both unaccepted by criteria. Though the intensities of the three kinds of current damp in turn, it only fits for the value of the top current, and so does the rotation angle of the top flex joint. It utilizes 1-year bottom data for the bottom current, and there is a little range for the bottom flex joint. It recommends choosing lower intensity bottom current for analysis and it may get a satisfactory result.

Table 1 Flex joint rotation angle under operational conditions /(°)

Current	Top		Bottom	
	Average	Maximum	Average	Maximum
1	3.42	4.95	5.85	7.27
2	2.50	3.94	5.77	7.05
3	2.00	3.42	5.75	7.08

1: 100-year Eddy+1year Bottom
2: 10-year Eddy+1year Bottom
3: 1-year Eddy+1year Bottom

5.1.3 Stress results

Table 2 presents that the maximum stress value in the analysis is in the range recommended by API criteria (53.6 ksi) according to the three current conditions. The stress is maximal both around the tensioner ring and at the bottom. It corresponds to the result of the previous effective tension and bending moment and demonstrates that the strength problem should be considered seriously at the two positions again.

Table 2 Maximum stress under operational conditions/ksi

Current	Maximum stress
100-year Eddy+1year Bottom	51.86
10-year Eddy+1year Bottom	51.65
1-year Eddy+1year Bottom	50.42

5.1.4 Top tension

Measures should be taken to avoid the over bulking and the maximum resistant load of tensioner due to the restraint of the top tension. The result in Table 3 shows that the top tension is in an accepted range.

Table 3 Maximum and minimum values of the top tension /kN

Current	Top tension	
	max	min
100-year Eddy+1year Bottom	1995.36	1670.64
10-year Eddy+1year Bottom	1986.02	1673.17
1-year Eddy+1year Bottom	1983.82	1674.31

5.2 Analysis of the hang-off condition result

5.2.1Effective tension and bending moment distribution

Figs.5~7 show the effective tension and bending moment on the above current conditions. It presents that the effective tension of risers reduces from up to down according to the static analysis results. The bending moment is maximum around the top out barrel, and this position relate to a peak value of the bending moment on operational condition. And since the bottom of the riser is free, the bending moment is nearly zero.

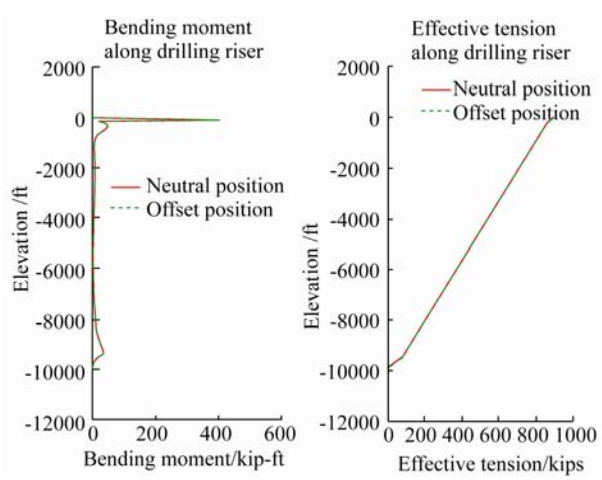

Fig.5 100-year Eddy+1year Bottom

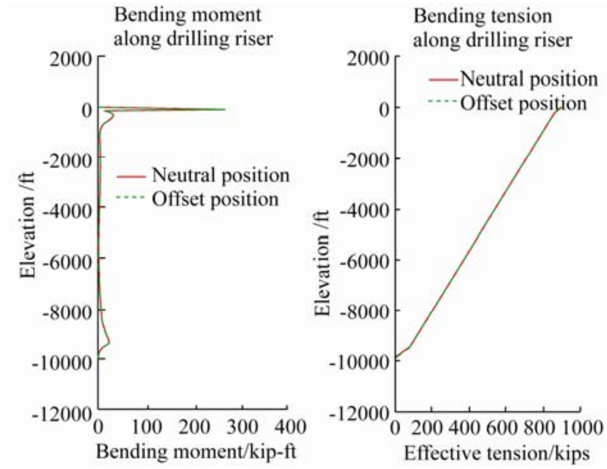

Fig.6 10-year Eddy+1year Bottom

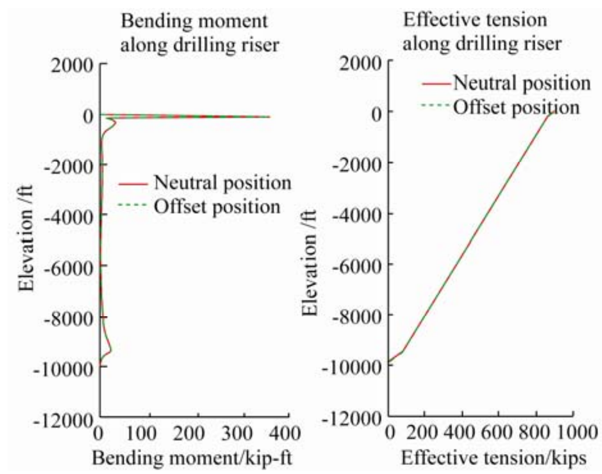

Fig.7 1-year Eddy+1year Bottom

It may affect the effective tension and bending moment to add an excursion to the top of the riser in the static analysis step, but the effect is very little. Also because of the free riser bottom, the effective tension and bending moment are mostly equivalent under static equilibrium condition. Different currents have little effect on effective tension, but the effect on the maximum bending is larger. The larger the current, the larger the maximum of the bending moment.

5.2.2 The rotation angles of flex joint

The rotation angle of the upper flex joint in Table 4 shows that the rotation angle under the 100-year Eddy+1 year Bottom current (the maximum is 11.29°) condition does not meet the requirement defined by criteria, while the other two meet the requirement. It presents that it is beneficial to reducing the rotation of the top flex joint so as to reduce the intensity of the top current.

The rotation angle of the lower flex joint, 0.42º, is much lower than the accepted value in criteria. Because the bottom is free, and the lower flex joint can move with the riser, but can’t withstand higher bending moment.

Table 4 Flex joint rotation angles under operational conditions /(º)

Current	Maximum rotation angle of the upper flex joint	Maximum rotation of the lower flex joint
1	11.29	0.42
2	9.42	0.42
3	8.48	0.42

1: 100-year Eddy+1year Bottom
2: 10-year Eddy+1year Bottom
3: 1-year Eddy+1year Bottom

5.2.3 Stress results

The stress calculation in Table 5 results show that, under the condition of hard hang-off, the maximum stress accords with the API specification proposed range (53.6 ksi). And the maximum stress locates at a place where the maximum bending moment occurs, which shows again that in the position where the stress is great and vulnerable to failure, the strength should be paid with more attention.

Table 5 Maximum stress under operating conditions/ksi

Currents	Maximum stress
100-year Eddy+1year Bottom	37.10
10-year Eddy+1year Bottom	31.92
1-year Eddy+1year Bottom	35.50

6 Conclusion

The main work of this article is, by using the FEA software, the static and dynamic analysis was conducted on the preliminary design of deep sea drilling riser, and the operating and hang-off condition. And the safety of it was checked in accordance with the code API 16Q. For the motion of the deepwater riser is non-liner, the time domain method is used in the dynamic analysis process.
In addition, the 3-D movement of the floater under the condition of combined wind and current, and the interaction of subsea riser and soil are taken into account. During each operating condition, the response of the riser under three kinds of current combined condition is considered. From the results of the calculation, the conclusion can be drawn as follows.

Under the operating condition, the stress and the top tension under the effect of the three kinds of current all meet the permitted codes; for the rotation angle of the upper flexible joint, only the average and the maximum values under the 1-year Eddy+1 year Bottom current conditions meet the demands, and for the rotation angle of the bottom flexible joint, neither the average nor the maximum value in three kinds of current combined state meets the requirements. Therefore, under such sea condition, the riser should not be on operating condition. And the modification of the riser design should be done to increase the thickness of the riser wall or the strength of the flexible joint. Also the analysis can be done under mild sea conditions so to make all the parameters meet the requirements given by the standards.

As to the hang-off conditions, all the stresses under the combined effects of these three kinds of current meet the requirements. For the rotation angle of the upper flexible joint, only the angle under the 100-year Eddy+1 year Bottom condition does not meet the requirements, the risers under other sea conditions are safe. For the rotation angles of the bottom flexible joint, they all meet the requirements, and also much less than the allowable value. Therefore, under the 10-year Eddy+1 year Bottom and 1-year Eddy+1 year Bottom Sea conditions, the hang-off condition is available.

The analysis of the effective tension and moment distribution along the riser shows that the peak value of the moment and stress will occur in the vicinity of the telescopic joint, where riser strength should be paid with more attention; In addition, under the operating condition, the effective tension is small at the riser bottom, but the moment will be extreme, which leads to great stress, so the local strength there should also be paid with more attention.

For the drilling riser, the role of the top tension cannot be ignored, in order to prevent the riser from overall buckling and the stress from exceeding the permitted value of the tensioner. The top tension must be controlled in a certain range.

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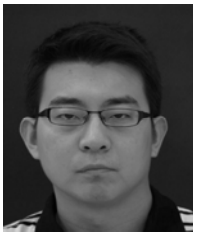

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操作与悬挂工况下的深海立管有限元分析

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摘　要：近年来，在深海进行油气开发的技术进展日新月异，全世界的海洋工程公司都在用更新的科技手段努力向更深的海域拓展，向深海进军已经成为了整个海洋石油工业的总体趋势. 作为连接平台设备和海底的重要设备，深海海洋立管的设计和使用也越来越趋向标准化. 该文以某深海立管为例，从操作工况和悬挂工况两个方面探讨了钻井立管的整体分析中遇到的主要问题并进行了相关的校核. 该文的具体工作包括计算了立管在钻探模态下的旋转角度和应力分布，确定了操作半径、浮箱数目等要素，并根据 API 规范进行了校核. 根据计算的结果可以看出，所选的立管在恶劣海况下的操作半径相对较小，而确定的浮箱数略多，相关结论对立管的初步设计具有较好的参考意义.

关键词：钻井立管；操作工况；悬挂工况；有限元分析