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Deep water drilling riser mechanical behavior analysis considering actual riser string configuration

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ABSTRACT

A dynamic analysis model considering the actual riser string configuration is established to analyze the mechanical behavior of a drilling riser. The riser in this model is regarded as a simply supported beam located in the vertical plane and is subjected to axial and lateral ocean environment loadings. The model is solved using the finite element method. The validity of the analysis model has been proved by a similar experiment conducted in a deep water basin and ANSYS. Riser lateral displacement, bending moment, and deflection of the deep water well considering actual riser string configuration in South China Sea are simulated. The effects of top tension, drilling platform drift distance, surface current speed, wave height, wave period, wave length, wind speed and damping coefficient on riser lateral displacement, bending moment, and deflection are also discussed. Results indicate that riser string configuration has a significant effect on riser mechanical behavior, particularly in the distribution of bending moment. Riser string configuration designing according to concrete ocean environment can significantly improve the riser's mechanical behavior. The distribution of riser lateral displacement, bending moment, and deflection increases with the increase in surface current speed and drilling platform drift distance, whereas decreases with the increasing top tension and damping coefficient. The distribution of riser lateral displacement, bending moment, and deflection significantly increases with the increase in surface current speed and large current speed may lead to large lateral displacement, bending moment, and deflection. Increasing top tension can significantly decrease riser mechanical behavior parameters and avoid large lateral displacement, bending moment, and deflection when suffering extreme ocean environment conditions in deepwater drilling field. Drilling platform should avoid a large drift distance, which may result in the deflection over the flex joint working range and the enlargement of the riser bend moment.

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1. Introduction

A deep-water drilling riser is a key equipment in deep-water drilling. Its major functions include connecting the subsea blowout preventer system and drilling platform, isolating sea water, establishing the circuitous path of the drilling fluid, and connecting additional pipelines. However, drilling risers below the telescopic joint are found in the seawater and under the effect of the ocean environment. Large deformation occurs under the effect of the ocean environment loads from the wind, wave, and current. Material strength theory states that the large deformation can expand the bending moment. The drilling riser may fracture if the bend moment cannot match the theory of material strength. This condition can trigger accidents and enormous economic losses. Thus, many researchers and manufacturers focus on the analysis of the mechanical behavior of deep-water drilling risers.

Scholars have conducted a number of theoretical studies on riser mechanical behavior. Burke (1973) performed a static analysis for marine riser using a beam model and showed that vessel response induced by waves could be a significant design factor for the dynamic behavior of the riser. Tucker and Murtha, (1973) employed the spectrum method to investigate drilling risers and considered the movement of drilling platforms. They found that the

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fundamental mode significantly contributes to the random response of the riser. Gardner and Kotch (1976) used the finite element method for the dynamic analysis of the riser and reported that the stress decreased with the increase in the top tension.

Azar and Soltveit (1978) developed a marine riser analysis model and considered the depth of seawater, density of the drilling fluid, and riser tension. Their studies showed the bending moment decreasing with increased top tension and water depth. Patel et al. (1984) investigated the mechanical behavior of a riser using the time domain method and compared this behavior with that observed through the frequency domain method for displacement and stress. Ahmad and Datta (1992) presented a frequency domain iterative procedure method for riser analysis and proved the frequency domain iterative method could be more efficient than the time integration method in riser analysis. Patel and Seyed (1995) comprehensively reviewed riser modeling and analysis techniques. Li (1996) simulated the response of the riser under wave-crest loads by combining the frequency domain and time domain methods and found the riser fatigue life of the threaded part near the water level. Atadan et al. (1997) considered the riser system and drilling platforms as a whole system and analyzed the riser and drilling platform system using the cantilever model. Their research demonstrated that the mass of the platform had an effect on the first resonance of the riser system. Chucheepsakul et al. (2003) introduced a new method to analyze the flexible marine pipes that could also be used in similar types of elastic structures, such as onshore pipes, submerged pipes, marine cables, onshore cables, and strings. Kaewunruen et al. (2005) employed Hamilton's principle to analyze the nonlinear free vibration of the riser and demonstrated that the internal flows could reduce the degree of the hardening of the risers. Athisakul et al. (2008, 2011) applied the finite element method to investigate the three-dimensional analysis of the extensible marine riser and revealed that the axial extensibility reduced the stability of the riser system. Pereira et al. (2006) simulated the influence of buoyancy on the mechanical behavior of a drilling riser and showed that the subsurface buoy significantly influenced riser dynamics. Guo et al. (2006a) built a dynamic model to discuss the effect of internal flow velocity on a riser and showed that the internally flowing fluid slightly influenced the dynamic characteristics of the riser. Passano and Maincon (2011) used nonlinear response predictor to examine the long-term distributions of the extreme response for a catenary riser and made the three long-term response distributions for risers. Jaculli et al. (2013) investigated the axial behavior of a drilling riser with a suspended mass and demonstrated that the maximum displacement in the suspended conditions might occur at any point along its length under different conditions. Liu et al. (2013, 2014) analyzed the influence of internal drilling pipe on the deformation of a drilling riser using the finite element method and concluded that the internal drilling pipe might inhibit the riser's deformation. Wang et al. (2014a, 2014b) established a dynamic model to analyze a marine riser during installation and suggested that the total riser stress gradually increased with the increasing speed of the float drilling platform. Qi et al. (2015) investigated the configuration of the drilling riser considering evacuation because of typhoon and recommended that the heavy wall thickness, such as 0.0254 m, and bare joint could be configured in the middle part of the riser system. de Aguiar et al. (2015) proposed a low computational cost methodology based on artificial neural networks for riser analysis and argued that the results were as reliable as those achieved from finite element models. Connaire et al. (2015) used quasi-rotations and the Newton–Raphson method for riser analysis and showed that the approach provided advantages for subsea riser sections. Li et al. (2015) analyzed the transverse vibration of the riser and indicated that the largest transverse displacement was found in the upper section of the riser. Major et al. (2015) studied the influence of drilling string rotation on the dynamic response of drilling risers and demonstrated that the drill string rotation reduced the natural frequency and increased the amplitude of the vibration of the drilling riser. Pham et al. (2016) comprehensively reviewed the manufacture, experimental investigations, and numerical analyses of deep-water risers.

Despite these studies, analyses on the mechanical behavior of deep-water drilling risers that consider the actual riser string configuration and variations in riser thickness and buoyancy are scarce. This study aims to investigate the mechanical behavior of deep-water drilling riser, considering the actual riser string configuration in the South China Sea. To investigate drilling riser mechanical behavior more thoroughly, a dynamic analysis model for drilling riser was established, and the model was solved through the finite element method combined with the Newmark-β method. A similar experiment was conducted in a deep-water basin at Shanghai Jiao Tong University to compare the results with those calculated from the analysis model. The mechanical behavior of the drilling riser of the deep-water well in South China Sea was analyzed in this study. The deformation, bending moment, and deflection of the drilling riser under different ocean environments were obtained. Riser mechanical behavior focuses on riser strength, whereas vortex induced vibration focuses on riser fatigue. Thus, vortex induced vibration (VIV) is neglected in this paper.

2. Analysis model

The riser close to the seabed is connected to the subsea blowout preventer stack through the lower flex joint. The riser near the water surface is connected to a diverter through the upper flex joint. The riser at the top ends can move with the drifting of the drilling platform, as shown in Fig. 1a. Thus, the mechanical model can be regarded as a simply supported beam located in the vertical plane. The simplified riser mechanical model in deep-water drilling can be expressed in Fig. 1b. However, the riser joint above the water surface has no ocean environment loadings. The riser differential control equation (Wilson, 2003; Guo et al., 2006b; Liu et al., 2013) can be represented as

$$
\begin{aligned}
&EI(y)\frac{\partial^4 x}{\partial y^4}+\left[m_\mathrm{f}V^2-T(y)\right]\frac{\partial^2 x}{\partial y^2}+2m_\mathrm{f}V\frac{\partial^2 x}{\partial y\partial t}+c\frac{\partial x}{\partial t}\\
&\quad+\left(m_\mathrm{r}+m_\mathrm{f}\right)\frac{\partial^2 x}{\partial t^2}\\
&\quad=F(y,t),
\end{aligned}
\tag{1}
$$

where $EI(y)$ is the bending stiffness of the riser along the y axis in $\mathrm{N\cdot m^2}$; m_f is the per unit length weight of the drilling fluid in kg/m; V is the velocity of the drilling fluid in m/s; $T(y)$ is the riser tension force distribution along the y axis in N; c is the damping coefficient of the riser; m_r is the per unit length weight of the riser in kg/m; and $F(y,t)$ is the lateral ocean environment force distribution along the y axis in N.

Riser string configuration is chiefly related with riser thickness and variation in buoyancy. These parameters mainly affect riser mechanical behavior through bending stiffness and tension on the cross section. The bending stiffness of the riser along the y axis can be depicted as

$$
EI(y)=E\cdot\frac{\pi\left[D_\mathrm{o}(y)^4-D_\mathrm{i}(y)^4\right]}{64},
\tag{2}
$$

where E is the elastic modulus of the riser in Pa; $D_\mathrm{o}(y)$ is the outer diameter of the riser along the y axis in m; and $D_\mathrm{i}(y)$ is the inner

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