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RESEARCH PAPER

A new type of anti-heave semi-submersible drilling platform

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Abstract: A new type of semi-submersible drilling platform is designed. The numerical simulation software is used to analyze the heave response of the new platform in the frequency domain and time domain, and the semi-submersible drilling platforms with double-floating four-column structure and heave plate structure are compared with the new platform. This paper introduces the design principles of the new platform and the theoretical basis, mathematical model and boundary conditions during correlation analysis. The numerical simulation results show that the maximum and mean values of the heave response of the new platform are significantly reduced in the frequency domain analysis compared with the double-floating four-column and the heave-plate structure platform; and the new platform has a significant increase in the natural heaving period of the new platform, which can effectively prevent the occurrence of resonance. In the mooring time domain coupling analysis, the surge, sway and roll response of the new platform is small, and the heave response is greatly reduced. In the spectral analysis, the new platform has a smaller peak response and better wave frequency characteristics. The new platform has excellent anti-heave performance, reasonable structure and feasibility, and can provide reference for the design and selection of new generation semi-submersible drilling platform.

Key words: drilling platform; semi-submersible drilling platform; heave prevention; frequency domain analysis; time domain analysis

Introduction

A drilling platform is important equipment for offshore oil and gas exploitation, of which a semi-submersible drilling platform with unique advantages becomes one of the platforms with the most promising development prospect[1–3]. In the marine environment, forces applied on a platform are in various forms[4–5], so it is difficult to analyze the overall performance of the platform with mathematical model, but hydrodynamic simulation is able to solve this problem[6]. The motion of platform in waves is nonlinear, which is caused by the coupling of different forms of motion (such as roll and heave coupling), the platform large-amplitude rolling and complex hydrodynamic loads[7]. The platform has six degrees of freedom in the marine environment[8], due to the structural characteristics of the semi-submersible drilling platform, the roll and heave responses have strong impacts on the safety of the platform[9] under the towing, operation and storm survival conditions, but the increase of additional mass can inhibit the roll and heave responses[10–11]. Non-linearity of roll motion can be simulated and studied by using chaos theory, differential dynamical system theory and bifurcation theory. There existing large safety hazard during normal drilling if the heave response is large, in order to reduce the impact of heave and ensure the constant contact of bit with well bottom, heave compensation device must be installed on the platform, which used telescopic drill pipe in the early stage, and now uses traveling compensation, crane compensation and winch compensation etc.[12]. At present, semi-submersible drilling platform has already developed the sixth generation which combines with the chain and the dynamic positioning system, can reduce the heave motion to some extent, but can not adapt to harsh sea conditions[13–14]. Therefore, a new type of semi-submersible drilling platform has been designed (referred to as the new platform), the performance of the new platform has been investigated with hydrodynamic numerical simulation, and compared with the original double floating four column structure platform (referred to as the original platform) and heave plate platform in this study.

1. Design of the new platform

1.1. Theoretical basis

When the ratio of the cross-sectional dimension of a structure to the wavelength is less than 0.2, the structure is called a small structure. Wave forces on it are dominated by inertial force and drag force, using a semi-theoretical and semi-empirical Morrison formula[15–16], the simplified calculation formula is:

$$\boldsymbol{F} = \rho V\left(\boldsymbol{I}_3 + \boldsymbol{C}_{\mathrm{a}}\right) v'_{\mathrm{w}} + 0.5\rho \boldsymbol{C}_{\mathrm{D}} v_{\mathrm{w}} \left|v_{\mathrm{w}}\right| e \tag{1}$$

When the ratio of cross-sectional dimension of a structure

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to the wavelength is greater than or equal to 0.2, three dimensional potential flow theory is taken[17] to do the analysis. The theory is an important basic theory for hydrodynamic analysis of structures, in which the velocity potential of fluid is particularly crucial. The total velocity potential includes the incident potential caused by the incident wave, the diffraction potential caused by the floating to the flow field, and the radiation potential caused by the perturbation of floating motion to the flow field, namely:

$$\Phi\left(x',y',z',t\right)=\Phi_{\mathrm{I}}\left(x',y',z',t\right)+\Phi_{\mathrm{D}}\left(x',y',z',t\right)+\Phi_{\mathrm{R}}\left(x',y',z',t\right) \tag{2}$$

1.2. Mathematical model

The force of current on the platform structure is:

$$F_{\mathrm{liu}}=0.5C_{\mathrm{d}}\rho A{v_{\mathrm{liu}}}^{2} \tag{3}$$

where the v_{liu} is the velocity of ocean current. The current velocity of the South China Sea is about 0.2m/s, so relative to wave force on the platform, the force of the ocean current on platform is negligible.

The wave force and torque of platform are respectively:

$$F_{\mathrm{wave}}=\frac{\pi^2r^2\rho HL}{T^2}C_{\mathrm{m}}\left(1-\mathrm{e}^{kh}\right)\sin\theta \tag{4}$$

$$M=\frac{\pi^2r^2\rho HLh}{T^2}C_{\mathrm{m}}\sin\theta\left(1-\frac{1-\mathrm{e}^{-kh}}{kh}\right) \tag{5}$$

Motion balance equation of platform under the wave load is:

$$\boldsymbol{M}_{\mathrm{m}}\boldsymbol{X}''+\boldsymbol{C}\boldsymbol{X}'+\boldsymbol{D}_1\boldsymbol{X}'+\boldsymbol{D}_2f(\boldsymbol{X}')+\boldsymbol{K}\boldsymbol{X}=\boldsymbol{F}_{\mathrm{sum}} \tag{6}$$

Determining the hydrodynamic parameter of the platform motion response in waves is the basis of the numerical calculation. When the platform is subjected to a slight oscillatory motion in a specific mode, an outward radiation flow field is generated in a stable flow field to form radiated waves[18]. Separating the velocity and acceleration of the corresponding structure from radiation wave load, we can get the parameters of the radiation wave load related to the velocity and acceleration, namely, additional damping parameter and additional quality parameter are collectively referred to as hydrodynamic parameters[18].

The radiation wave load force is:

$$F_{jpq}=\iint\limits_{S_j}\boldsymbol{p}_{jp}\cdot\boldsymbol{n}_j\mathrm{d}s$$

$$(j=1,2,\cdots,N;\ p=1,2,3;\ q=1,2,3) \tag{7}$$

where the $\boldsymbol{p}_{jp}$ is pressure vector at any point in flow field, determined by Bernoulli's equation[18].

The relation between radiation wave force and hydrodynamic parameters is:

$$F_{jpq}=-A_{jpq}v'_{jp}-B_{jpq}v_{jp} \tag{8}$$

With further analysis, the calculation formulas of hydrodynamic parameters are:

$$A_{jpq}=-\mathrm{Re}\left(\frac{F_{jpq}}{v'_{jp}}\right) \tag{9}$$

$$B_{jpq}=-\mathrm{Re}\left(\frac{F_{jpq}}{v_{jp}}\right) \tag{10}$$

1.3. Boundary conditions

1.3.1. Platform displacement boundary conditions

To avoid rigid displacement of the model, displacement boundary conditions are required in the analytical model, that is to say, 3 non-collinear nodes with great strength far away from platform structure evaluation area should be chosen to fix the structure. Displacement boundary conditions are applied at the selected nodes: node 1 restricts z direction displacement; node 2 restricts y and z direction displacement; node 3 restricts x, y, and z direction displacement.

1.3.2. Mooring boundary conditions

① Statics boundary conditions. For the upper end of the mooring anchor:

$$v\left(l=L_{\mathrm{a}}\right)=v_{\mathrm{top}} \tag{11}$$

For lower end of the mooring anchor:

$$v\left(l=0\right)=v_{\mathrm{bot}} \tag{12}$$

② Dynamic boundary conditions. For the upper end of the mooring anchor:

$$\begin{cases}v\left(l=L_{\mathrm{a}}\right)=v_{\mathrm{top}}\\ v'\left(l=L_{\mathrm{a}}\right)=v'_{\mathrm{top}}\end{cases} \tag{13}$$

For lower end of the mooring anchor:

$$\begin{cases}v\left(l=0\right)=v_{\mathrm{bot}}\\ v'\left(l=0\right)=v'_{\mathrm{bot}}\end{cases} \tag{14}$$

1.3.3. Flow field boundary conditions

① Free surface boundary conditions. At each point of the free surface:

$$\frac{\partial^2\Phi}{\partial t^2}+g\frac{\partial\Phi}{\partial z}=0 \tag{15}$$

In the local coordinate system, column surface immersed in sea water should meet the requirements of:

$$\begin{cases}\dfrac{\partial\Phi}{\partial z}=0\\[2mm] \dfrac{\partial\Phi}{\partial r}=0\end{cases} \tag{16}$$

②Surface boundary conditions. Instantaneous normal acceleration of fluid particle is zero for the area where surface total force is zero:

$$\nabla^2\Phi=0 \tag{17}$$

③ Seabed boundary conditions. Seabed as a rigid wall, normal velocity component of the fluid particle is zero.

④ Radiation conditions of infinite point. Wave forms spread from near to far, that is when r approaches infinity, $\nabla\Phi$ approaches zero.

1.4. Design principle

Since the external excitation time cannot be controlled, in