Dynamic Response of High-Pressure Riser of Deepwater Surface Blowout Preventer System

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Abstract
The application of surface blowout preventer (SBOP) drilling system in deepwater environments has been demonstrated that it can save operation cost and time. The high pressure small diameter casing plays the role of the conventional riser and bears the complex loading caused by the wave and current force and drilling platform motion. The coupled quasi-static and uncoupled dynamic analysis models of deepwater SBOP drilling system were established. The analysis results indicate that the uncoupled method without consider the lateral offset on the end of the high pressure riser nearly no affection to the riser analysis. However, the uncoupled method has a certain impact on the mechanical analysis of the subsea wellhead and the casing string under mudline. The lateral offset of the high pressure riser changes greatly in the different times, the bending moment of the upper and lower stress joint of riser is bigger. The platform long-term drift has a greater impact on the dynamic response analysis of the high pressure riser of SBOP system for deepwater drilling.

Keywords: deepwater drilling, surface blowout preventer, high pressure riser, stress joint, dynamic response

1. Introduction
The surface blowout preventer (SBOP) system application on drilling platform is a well established drilling technology in deepwater environments. It has illustrated considerable amount of day rate and time savings over traditional drilling method using subsea BOP and low-pressure riser system [1-9]. The equipments of SBOP drilling system consist of surface blowout preventer stack, surface wellhead, upper stress joint, high pressure small diameter riser, subsea disconnection device and control system(SDS), lower stress joint, subsea wellhead, and so on. These equipments using in deepwater have some difference with its using in land or shallow water environments. The high pressure small diameter casing as the conventional riser bears complex loading caused by wave force and etc.
2. High-Pressure Riser Quasi-Static Coupling Analysis

2.1. Theoretical Models of Quasi-Static Coupling Analysis

Due to the high-pressure riser transfers the force of the marine environment load to the subsea wellhead and the casing string below mud line, a coupling analysis for the high-pressure riser and the casing string below mud line is necessary to used. The riser and casing string are supposed as the line elastic tube, only have a small distortion in the role of external forces, and ignoring the impact of the drill string. According to the mechanics of materials theory can establish a coupled quasi-static analysis model of deepwater SBOP system \[10-12\] as equation 1.

\[
\begin{align*}
\frac{d^2}{dx^2} \left( E_r I_r \frac{d^2 y}{dx^2} \right) - \frac{d}{dx} \left( T(x) \frac{dy}{dx} \right) - W(x) \frac{dy}{dx} &= F(x), \quad 0 \leq x \leq L_r \\
\frac{d^2}{dx^2} \left( E_c I_c \frac{d^2 y}{dx^2} \right) + \frac{d}{dx} \left( N(x) \frac{dy}{dx} \right) + D_s(x) p(x, y) &= 0,
\end{align*}
\]

where, \( x \) is the direction along the depth, \( m \). \( y \) is the lateral offset of the riser, \( m \). \( E_r \) is the elastic modulus of the riser, \( \text{kPa} \). \( I_r \) is the moment of inertia of riser, \( m^4 \). \( T \) is the effective tension of riser, \( \text{kN} \). \( W \) is the weight per unit length of riser (including internal drilling fluid), \( \text{kN} \). \( F \) is the wave and current quasi-static force acting on the riser, \( \text{kN} \). \( E_c \) is the elastic modulus of the casing string below the mud line, \( \text{kPa} \). \( I_c \) is the moment of inertia of casing, \( m^4 \). \( N \) is the axial force along the casing string, \( \text{kN} \). \( D_s \) is the diameter of casing string, \( m \). \( p(x, y) \) is the reaction force on the foundation, \( \text{kPa} \). \( L_r \) is the length of riser, \( m \). \( L_{SDS} \) is the height of the SDS, \( m \). \( L_{sc} \) is the length of the casing string, \( m \).

The boundary conditions for the theoretical models of coupling analysis are shown as equation 2.

\[
\begin{align*}
M \big|_{x=L_r} &= K_{r1} \theta_{r1}, \quad y \big|_{x=L_r} = S_0 \\
M \big|_{x=0} &= K_{r2} \theta_{r2}, \quad y \big|_{x=0} = y_r \\
M \big|_{x=-L_{SDS}} &= -M_0, \quad Q \big|_{x=-L_{SDS}} = -H_0 \\
M \big|_{x=-(L_{SDS}+L_{sc})} &= 0, \quad Q \big|_{x=-(L_{SDS}+L_{sc})} = 0
\end{align*}
\]

where, \( M_0 \) is the bending moment on the subsea wellhead, \( \text{kN} \cdot \text{m} \). \( H_0 \) is the lateral force on the subsea wellhead, \( \text{kN} \). \( K_{r1}, K_{r2} \) are the rotational stiffness of the upper and lower stress joint, \( \text{kN} \cdot \text{m} / \text{rad} \). \( \theta_{r1}, \theta_{r2} \) are the offset angle of the upper and lower stress joint, \( \text{rad} \). \( S_0 \) is the platform drift, \( m \). \( y_r \) is the lateral displacement of the end of lower stress joint, \( m \).

The finite difference methods is adopted to solve these equations\(^{[10]}\). Then the rotation angle, the bending moment, the shearing force, the soil reaction along casing string according to the displacement were obtained.

2.2. Compare the Coupled Method with Uncoupled Method

The base parameters for simulation are shown in as follows. Water depth is 1200m, the outer diameter of high pressure riser is 339.7mm and the wall thickness is 14.25 mm.

The top tension ratio (TTR) of the riser is 1.3, the offset of drilling platform is 36m. The current velocity on sea level is 1.0m/s, the tide velocity on sea level is 0.5m/s, the wave height is 8m. The mud density is 1.2g/cm\(^3\), the height of SDS is 8.0m and the weight of SDS is 50.0t.

The rotational stiffness of the upper and lower stress joint are 500kN·m/\text{rad} respectively. The distance from wellhead to mud line is 3.0m, the length of conductor is 50m, and its outer diameter is 609.6 mm. the length of surface casing is 600m, and its outer diameter is 339.7mm.

The soil type below the mud line 0-60m is clay, the mean value of untrained shear strength is 20.0Kpa, and the mean value of submerged unit weigh is 7.0kN/m\(^3\).
Generally, the riser mechanical analysis without considering the coupling relationship of the riser and the casing string below mud line. The results of compared the coupled method with uncoupled method are shown in Figure 1 and Table 1.

Can be seen from Figure 1, the analysis results of the coupled and uncoupled method are similar, and the uncoupled method without consider the casing string below mud line nearly no affection to the riser analysis. This is the main reason to simplify the analytical model of the drilling riser.

However, as show in table 1, the uncoupled method has a certain impact on analysis to the subsea wellhead and casing string.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Uncoupled method</th>
<th>Coupled method</th>
<th>Absolute error</th>
<th>Relative error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>the lateral displacement of the end of lower stress joint /m</td>
<td>0.00</td>
<td>0.22</td>
<td>0.22</td>
<td>/</td>
</tr>
<tr>
<td>the offset angle of the end of lower stress joint /°</td>
<td>11.10</td>
<td>11.08</td>
<td>0.02</td>
<td>0.19</td>
</tr>
<tr>
<td>the lateral displacement of the subsea wellhead /m</td>
<td>0.030</td>
<td>0.032</td>
<td>0.002</td>
<td>5.010</td>
</tr>
<tr>
<td>the bending moment of the subsea wellhead /kN.m</td>
<td>896.24</td>
<td>929.63</td>
<td>33.39</td>
<td>3.73</td>
</tr>
<tr>
<td>the offset angle of the subsea wellhead /°</td>
<td>0.63</td>
<td>0.60</td>
<td>0.03</td>
<td>4.48</td>
</tr>
</tbody>
</table>

3. The Dynamics Response of High-Pressure Riser

3.1. Theoretical Models of Dynamic Analysis

Because the uncoupled method without consider the casing string below mud line nearly no affection to the riser analysis, then according to the mechanics of materials and structural dynamics theory, a dynamics model of high pressure riser of SBOP system was established [13-14], show in equation 3.

$$m(x) \frac{d^2 y(x,t)}{dt^2} + c(x) \frac{dy(x,t)}{dt} + \frac{d^2}{dx^2} \left[ E_x I_x(x) \frac{d^2 y(x,t)}{dx^2} \right]$$

$$- \frac{d}{dx} \left( T(x) \frac{dy(x,t)}{dx} \right) - W(x) \frac{dy(x,t)}{dx} = F_{dc}(x,t)$$

where, $m$ is the mass per unit length of the riser (including internal drilling fluid), kg. $c$ is the structure damping coefficient. $F_{dc}$ is the wave and current dynamical force acting on the riser, kN.
P-M spectrum was adopted to describe the random wave. It has been widely used in structure dynamic response of ocean engineering. As shown in equation 4.

$$S_n(\omega) = \frac{0.78}{\omega} \cdot \frac{H^2_{1/3}}{\omega^{3/2}} e^{-\frac{3.11}{\omega^2 H^2_{1/3}}}$$

(4)

where, $\omega$ is the circular frequency, rad/s. $H_{1/3}$ is the significant wave height, m. $S_n$ is the unilateral spectrum density, m$^2$/s.

The wave height variation with time in deepwater is shown in equation 5.

$$\eta(x,t) = \sum_{i=1}^{n} \sqrt{2S_n(\omega)} d\omega \cos(\omega t - \phi_i)$$

(5)

where, $\eta(x,t)$ is the instantaneous wave height, m. $\phi_i$ is the initial phase of each component wave, rad.

Drilling platform would move by the first order wave force and the two order wave force. According to the literature data$^{[15]}$, the drilling platform motion model is shown in as equation 6.

$$S(t) = S_0 + S_L \sin(2\pi t / T_L) + \sum_{i=1}^{n} S_n \cos(k_n S(t) - \omega_n t + \phi_n + \alpha_n)$$

(6)

where, $S_0$ is the mean offset of platform, m. $S_L$ is the drift amplitude of platform, m. $T_L$ is the drift period of platform, s. $S_n, k_n, \omega_n, \phi_n, \alpha_n$ are the wave amplitude, wave number, circular frequency, initial phase and phase difference of the wave $n$.

The wave force on the riser could be calculated by Morison equation. The model considering the current influence is shown in as equation 7.

$$F_{wL}(x,t) = \frac{\pi}{4} \rho_w C_D D_s^2 \frac{\partial u_w(x,t)}{\partial t} - \frac{\pi}{4} \rho_w (C_M - 1) D_s^2 \frac{\partial^2 y(x,t)}{\partial t^2}$$

$$+ \frac{1}{2} \rho_w C_D D_s (u_w + u_c) \left| \frac{\partial y(x,t)}{\partial t} \right| u_w + u_c$$

(7)

where, $\rho_w$ is the seawater density, g/cm$^3$. $D_s$ is the outer diameter of high pressure riser, m. $C_D, C_M$ are the drag and inertia coefficient respectively. $u_w, u_c$ are the wave and current velocity, m/s.

The finite difference method was used to solve the dynamics model of the high pressure riser of SBOP system. And a software was programmed which convenient for engineering applications$^{[16], [17]}$.

3.2. Example Case

The length of drill pipe in the water is 1200m, the outer diameter of drill pipe is 339.7mm, the wall thickness is 108.6mm, and the top tension ratio is 1.3. The drilling fluid density is 1.2g/cm$^3$, the mean drift of platform is 36m, the current velocity is 1.0 m/s, the tide velocity is 0.5m/s. the wave spectrum is P-M spectrum, the effective wave height is 8m.

The high pressure riser analysis without coupled with the casing string below mud line, then above theoretical equations 3 to 5 were used to analyses this example.

3.3. The Lateral Offset and Bending Moment of The High Pressure Riser in Time Domain

As illustrate in Figure 2, the maximum lateral offset of the high pressure riser changes from 45m to 65m on the region below the sea level 500m in the different times. The bending moment of the high pressure are similar in the different times, but the bending moment of the upper and lower stress joint of riser is bigger, need to enhance the stress joint strength.
3.4. The Bending Moment and Angle Response on the Top/End of HP Riser

Figure 3 shows the bending moment on the top of high pressure riser as sine curve. The amplitude of curve is between 34-47KN·m. It indicates that the platform long-term drift has some affection on the top of high pressure riser.

Figure 4 shows that the angle on the end of high pressure riser appeared as sine curve. The amplitude of curve is between 10-12°. It indicates that the platform long-term drift has a greater impact on the dynamic response analysis of the end of SBOP high pressure riser.
4. Conclusion

Generally, the uncoupled method without considering the lateral offset on the end of riser nearly no affection to the riser analysis. However, the uncoupled method has a certain impact on analysis to the subsea wellhead and casing string.

The lateral offset of the high pressure riser changes greatly in the different times, and the bending moment of the high pressure are similar in the different times, but the bending moment of the upper and lower stress joint of riser is bigger.

The platform long-term drift has a greater impact on the dynamic response analysis of the SBOP high pressure riser.

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