Numerical Simulation Analysis on the Lateral Dynamic Characteristics of Deepwater Conductor Considering the Pile-Soil Contact Models

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Abstract: It is important to accurately assess the interaction between the conductor and the soil to ensure the stability of the subsea wellheads during deepwater drilling. In this paper, numerical simulations were carried out to study the lateral dynamic bearing capacity of the conductor considering different contact models between the conductor and the soil. In particular, the contact surface model and contact element model were selected to study the dynamic behavior of pile–soil under a transverse periodic load. On this basis, the influence of the bending moment, the wellhead stick-up, the outer diameter (O.D.) of the conductor and the wall thickness (W.T.) of the conductor, as well as the physical parameters of the soil on the dynamic bearing capacity are discussed in detail. Analysis results show that the lateral deformation, deflection angle and von Mises stress calculated by the contact surface model are greater than those calculated by the contact surface model. The maximum value of the lateral deformation and bending moment of the conductor decrease with the O.D. and W.T. of the conductor, and the cohesion and internal friction angle of the soil. However, the maximum value of the lateral deformation and bending moment of the conductor increase with the wellhead stick-up. Both the vertical force and the soil density have a negligible effect on the lateral behavior of the conductor. This study has reference value for the design and stability assessment of subsea wellheads.

Keywords: deepwater conductor; lateral dynamic characteristics; pile–soil interaction models; subsea wellhead stability; numerical simulations

1. Introduction

In deepwater drilling, the conductor is installed by the jetting method where the conductor is not cemented in most cases. As a result, the conductor is in direct contact with the soil. After completion of the conductor, the lower marine riser package (LMRP) and the blowout preventer (BOP) will be run into the sea water through the drilling riser [1]. After installation of the LMRP and BOP, the riser is subjected to a lateral dynamic load induced by the sea wave and current. The load acting on the riser will eventually transmit to the conductor through the LMRP and BOP, which will cause mechanical deformation of the conductor, as shown in Figure 1. Considering the significance of the subsea wellhead stability, it is important to accurately assess the interaction between the conductor and the soil. Generally, the bearing capacity of the conductor belongs to the pile–soil interaction issue. Thus, the pile–soil contact models are essential for accurate assessment of the conductor-bearing capacity. Otherwise, an unexpected mechanical deformation will be generated if the bearing capacity of the conductor is not sufficient, which will inevitably bring about instability of the subsea wellhead, and even lead to drilling accidents as well as economic losses [2].
At present, many scholars have carried out research on the bearing capacity of the conductor. The static mechanical behavior has been studied to calculate the lateral bearing characteristics in soft clay formation [3-8]. With the gradual increase in the water depth, the dynamic load on the drilling riser becomes more and more complex. Thus, the dynamic bearing capacity of the conductor has attracted ever more attention. The influence of the time effect [9, 10], sand liquefaction [11] and earthquakes [12] on the dynamic characteristics have been studied based on the P-y model [13]. In addition, the theoretical analysis of pile-soil interaction has been studied through simplifying the conductor into the Euler–Bernoulli beam [14]. Additionally, numerical simulations of the pile-soil interaction have also been conducted [15-18]. The effect of the external load [19] and pile-soil characteristics [20-26] on the bearing capacity of the conductor have also been investigated according to the P-y model.

Although the P-y model was used in previous studies, it needs to be improved if we are considering the pile vibration and soil detachment [27]. Therefore, some new pile-soil interaction models have been put forward to overcome the shortcomings of the P-y model [28-33]. Among these proposed models, the Goodman contact element model is able to consider the displacement discontinuity of the contact interfaces, which has good applicability in pile-soil interaction simulations [33]. Therefore, numerical simulations were carried out in this paper to assess the influence of pile-soil contact models on the lateral dynamic bearing capacity of deepwater conductors.

2. Pile–Soil Contact Models

Normally, the pile-soil interaction involves a series of nonlinear problems. Therefore, it is important to select an appropriate pile-soil contact model to assess the pile-soil interaction. Due to the mechanical properties of the conductor and the soil, bonding or closing, slipping or opening may occur during the pile-soil interaction, as shown in Figure 2.
2.1. Contact Surface Model

2.1.1. Normal Contact Model

Generally, the normal contact model is one of the commonly used contact surface models, which is also called the contact pressure-interference model, and includes two types of models: the hard contact model and the soft contact model. The hard contact model can be represented by the Lagrange multiplier method in the form of virtual work, which is shown in Equation (1) and Figure 3.

$$\delta \Pi = \delta ph + p \delta h$$  \hspace{1cm} (1)

As shown in Figure 3a, if the interference between these two surfaces is negative ($h < 0$), there is no normal pressure on the contact surface ($p = 0$). If the interference is zero ($h = 0$), normal pressure will generate on the contact surface ($p > 0$). The mechanical behavior of the soft contact model is shown in Figure 3b, which can be described by the exponential relationship, as shown in Equation (2).

$$\begin{cases} p = 0, & h \leq -c_0 \\ p = \frac{p_0}{e-1} \left[ \frac{h}{c} + 1 \right] \left[ \left( \frac{h}{c e^x} + 1 \right) - 1 \right], & h > -c_0 \end{cases}$$  \hspace{1cm} (2)

As shown in Figure 3b, the normal pressure changes with the clearance of the contact surfaces, which means that the normal pressure will generate on the contact surfaces when the clearance is not yet zero.

![Figure 3](image1.png)

Figure 3. Mechanical behavior of different contact models, where (a) is the hard contact model in normal contact model, (b) is the soft contact model in normal contact model, and (c) is the tangential contact model.

2.1.2. Tangential Contact Model

Normally, the tangential contact model can be described by the Coulomb criterion, as shown in Figure 3c. When the equivalent frictional stress reaches the critical value, relative sliding will occur on the contact surfaces. In addition, the tangential friction behavior is isotropic and the sliding direction can be defined by the friction stress direction.
2.2. Goodman Contact Element Model

The Goodman contact element model is a non-thickness element with four nodes (No. 1, No. 2, No. 3, and No. 4) and eight degrees of freedom [28,34], which are shown in Figure 4.

![Goodman contact element model](image)

Figure 4. Goodman contact element model.

In this model, springs are arranged on the normal and tangential direction of the contact surfaces (surface 1–2 and surface 3–4) to simulate the normal and tangential behavior. The normal and tangential pressure is related to the corresponding displacement of the contact surface. The constitutive model of the Goodman contact element model can be written by Equation (3).

\[
\begin{bmatrix}
\sigma_n \\
\tau_z
\end{bmatrix} = 
\begin{bmatrix}
k_n \\
0
\end{bmatrix} 
\begin{bmatrix}
\varepsilon_n \\
\gamma_z
\end{bmatrix}
\]  

(3)

The node displacement of the element can be written as:

\[
\begin{bmatrix}
\varepsilon_n \\
\gamma_z
\end{bmatrix} = 
\begin{bmatrix}
a & 0 & b & -b & 0 & -a & 0 \\
0 & a & 0 & b & 0 & -b & 0 & -a
\end{bmatrix} \begin{bmatrix}
\delta^e
\end{bmatrix}
\]  

(4)

where, \( \delta^e = (u_1 \quad v_1 \quad u_2 \quad v_2 \quad u_3 \quad v_3 \quad u_4 \quad v_4)^T \); \( u_i (i = 1,2,3,4) \) and \( v_j (i = 1,2,3,4) \) are the horizontal and vertical displacement of the nodes; \( a = \frac{1}{2} - \frac{x}{L} \); \( b = \frac{1}{2} + \frac{x}{L} \).

The relation between the force and displacement of the node can be calculated by Equation (5), which is:

\[
\{F\}^e = [K]^{e} \{\delta\}^e
\]

where,

\[
[K]^{e} = \frac{L}{6} 
\begin{bmatrix}
2k_s & 0 & k_s & 0 & -k_s & 0 & -2k_s & 0 \\
0 & 2k_n & 0 & k_n & 0 & k_n & 0 & -2k_n \\
0 & k_n & 0 & 2k_s & 0 & -2k_s & 0 & k_s \\
-2k_s & 0 & -k_s & 0 & 2k_s & 0 & k_s & 0 \\
0 & k_n & 0 & -2k_n & 0 & 2k_n & 0 & k_n \\
0 & -2k_n & 0 & -k_n & 0 & k_n & 0 & 2k_n
\end{bmatrix}
\]

The Goodman contact element model can simulate the dislocation slipping, the expansion of the contact surface, and the nonlinear characteristics of the contact surface deformation. Besides, the Goodman contact element model can simulate the state before the relative slip on both sides of the contact surface. The normal stiffness of the Goodman contact element is determined by the empirical value, and the tangential stiffness can be determined by the shear tests of the pile and soil. In this paper, the user subroutine for the Goodman contact element model is coded with Fortran language in ABAQUS software.
3. Numerical Simulation and Discussion

3.1. Numerical Simulation

3.1.1. Modeling Process

(1) Geometric model

The deepwater conductor parameters and the soil parameters are shown in Table 1 and Table 2. Based on the data, a three-dimensional (3-D) finite element (FE) model of pile-soil interaction was established. In order to eliminate the boundary effect, the O.D. and thickness of the soil are set 20 and 1.5 times the O.D. and length of the conductor, respectively.

Table 1. Conductor parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (m)</td>
<td>1000</td>
<td>Elasticity modulus (GPa)</td>
<td>210</td>
</tr>
<tr>
<td>Wellhead stick-up (m)</td>
<td>5</td>
<td>Density (kg/m$^3$)</td>
<td>7800</td>
</tr>
<tr>
<td>Penetration depth (m)</td>
<td>60</td>
<td>Weight of BOP (t)</td>
<td>200</td>
</tr>
<tr>
<td>O.D. of the conductor (in)</td>
<td>36</td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>W.T. of the conductor (in)</td>
<td>1</td>
<td>Maximum bending moment on the conductor (kN·m)</td>
<td>3000</td>
</tr>
</tbody>
</table>

Soil damping is an important parameter which needs to be specified. Since the Rayleigh damping has good applicability in numerical simulation, it is adopted to simulate the soil damping characteristics in this paper. The mathematical expression of the Rayleigh damping can be written as:

$$\{C\} = \alpha_0\{M\} + \alpha_1\{K\} \quad (6)$$

In order to ensure the rationality and feasibility of the damping matrix, some specific principles must be observed while choosing $\alpha_0$ and $\alpha_1$. In this paper, $\alpha_0$ and $\alpha_1$ are 0.2 and 0, respectively.

During the whole simulation process, all degrees of freedom (DOF) of the soil bottom surface are completely constrained. The lateral surface of the soil is constrained in both horizontal and vertical directions. A reference point (RP) is set on the top of the conductor. The coupling connection is established between the RP and the conductor top surface, which is used to apply the vertical force and bending moment to the conductor. The conductor and the soil are meshed by C3D8 solid element [18]. The 3-D FE models after the completion of boundary conditions, loading and meshing are shown in Figures 5–7, respectively.
Figure 5. The 3-D FE model after completion of boundary conditions (cross-section view).

Figure 6. The 3-D FE model after completion of loading.

Figure 7. The 3-D FE model after completion of meshing.

3.1.2. Simulation Results

The contact surface model and Goodman contact element model are used to study the dynamic bearing capacity of the conductor. The dynamic bending moment on the top of the conductor is \( M_t = 3000 \sin \frac{\pi}{5}(t - 0.2) \) (kN \( \cdot \) m), and the vertical force is 2000 kN. When \( t = 22.7 \) s, the lateral deformation and von Mises stress obtained by the two models are shown in Figures 8–10, respectively.

As shown in Figures 8 and 9, the lateral deformation decreases sharply along the axial direction of the conductor. In this case, the maximum lateral deformation of the conductor calculated by the contact surface model and the Goodman contact element model is \( 6.593 \times 10^{-2} \) m and \( 6.977 \times 10^{-2} \) m. For specific nodes, the lateral deformation calculated by the Goodman contact element is greater than that calculated by the contact surface model. The force on the wellhead and the lateral deformation on the top of the
The conductor calculated by the two models reach their maximum value simultaneously. As shown in Figure 10, the maximum von Mises stress calculated by the contact surface model and the Goodman contact element model are 141.8MPa and 142.1Mpa while the minimum von Mises stress calculated by the two models are 111.4MPa and 13.25Mpa. Therefore, a conclusion to draw is that the pile–soil contact model has influence on the dynamic mechanical response of the conductor.

Figure 8. Simulation results of the lateral deformation, where (a) is the result calculated by the contact surface model and (b) is that calculated by the Goodman contact element model.

Figure 9. The lateral deformation along the conductor axial direction, where (a) is the result calculated by the contact surface model and (b) is that calculated by the Goodman contact element model.

Figure 10. The von Mises stress of the conductor, where (a) is calculated by the contact surface model and (b) is calculated by the Goodman contact element model.
3.2. Model Validation and Mesh Independence

In order to verify the correctness of the model established in this paper, we made a comparative analysis of the vertical bearing capacity of the 762 mm and the 914.4 mm conductor and the published literature [35]. The vertical bearing capacity of the conductor through the theoretical analysis model, contact surface model and Goodman contact element model was compared and analyzed, as shown in Figure 11.

![Figure 11. Model verification results.](image)

As shown in Figure 11, the results obtained in this work are in good agreement with Su’s work. Under the three analysis methods, the vertical bearing capacity of the conductor increases with the jetting depth. The results calculated by the Goodman contact element model are smaller than those calculated by the contact surface model, which is also consistent with the published literature [18]. Thus, the correctness of the model established in this paper is verified. In addition, we carried out the mesh independence. The conductor and the soil are meshed by the C3D8 solid element. We used a normal grid, a refined grid and a sparse grid to study the influence of the grid number on the bearing capacity of the conductor. We found that if the refined grid is used in a radial range five times the diameter of the conductor, the number of the mesh has a negligible effect on the bearing capacity of the conductor.

3.3. Parameter Sensitivity Analysis

3.3.1. Bending Moment on the Top of the Conductor

If the O.D. and W.T. of the conductor are 36 in and 1 in, the wellhead stick-up is 5 m, the bending moment on the top of the conductor is $2000\sin\frac{\pi}{5}(t - 0.2)(\text{kN} \cdot \text{m})$, $3000\sin\frac{\pi}{5}(t - 0.2)(\text{kN} \cdot \text{m})$ and $4000\sin\frac{\pi}{5}(t - 0.2)(\text{kN} \cdot \text{m})$; the lateral deformation and bending moment are shown in Figure 12.
Figure 12. The influence of the bending moment on the mechanical response of the conductor, where (a) is the variation of the lateral deformation at the top of the conductor with time and (b) is the variation of the bending moment along the conductor axial direction when the maximum bending moment is 4000 kN-m.

As shown in Figure 12, the lateral deformation of the conductor presents periodic distribution under the action of the harmonic bending moment. In addition, the bending moment increases initially and then decreases along the conductor axial direction. In this case, the maximum lateral deformation under these three conditions is 0.0424 m, 0.0696 m, and 0.0989 m, respectively. The maximum bending moment of the conductor is 4129 kN-m when the maximum bending moment is 4000 kN-m, which appears 6 m below the top of the conductor.

3.3.2. Wellhead Stick-Up

If the O.D. and W.T. are 36 in and 1 in, the bending moment on the top of the conductor is $3000 \sin \frac{n}{5} (t - 0.2) (\text{kN} \cdot \text{m})$, the vertical force is 2000 kN, and the wellhead stick-up changes from 4 m to 6 m; the calculated lateral deformation and bending moment are shown in Figure 13.

Figure 13. The influence of wellhead stick-up on the mechanical response of the conductor, where (a) is the variation of lateral moment at the top of the conductor with time and (b) is the variation of bending moment along the conductor axial direction when the wellhead stick-up is 6 m.

As shown in Figure 13, both the maximum lateral deformation and the maximum deflection angle increase with the wellhead stick-up. In this case, the maximum lateral deformation is 0.0559 m, 0.0696 m, and 0.0833 m when the wellhead stick-up is 4 m, 5 m
and 6 m, which means that the bending moment is an unfavorable factor for the stability of the subsea wellhead. In addition, the maximum lateral deformation and deflection angle along the conductor axial direction also increase with the wellhead stick-up. The depth where the bending moment reaches its maximum value increases with the conductor length.

3.3.3. Geometry of the Conductor

The O.D. of the conductor widely used is 30 in and 36 in, and the W.T. is 1 in and 1.5 in. In this section, we will discuss the influence of the O.D. and W.T. on the lateral dynamic response. When the bending moment is $3000 \sin \frac{\pi}{2} (t - 0.2) (\text{kN} \cdot \text{m})$ and the vertical force is 2000 kN, the results are shown in Figures 14 and 15.

![Figure 14](image1.png)

**Figure 14.** The influence of O.D. on the mechanical response of the conductor, where (a) is the variation of the lateral moment at the top of the conductor with time and (b) is the variation of the bending moment along the conductor axial direction when the O.D. and W.T. are 36 in and 1.0 in, respectively.

![Figure 15](image2.png)

**Figure 15.** The influence of the W.T. on the mechanical response of the conductor, where (a) is the variation of the lateral moment at the top of the conductor with time and (b) is the variation of the bending moment along the conductor axial direction when the O.D. and W.T. are 36 in and 1.5 in, respectively.

As shown in Figures 14 and 15, the maximum lateral deformation is 0.1013 m and 0.0648 m when the O.D. of the conductor is 30 in and 36 in, respectively. In addition, the deflection angle at the top of the conductor decreases with the O.D. and W.T. of the conductor. However, the bending moment of the conductor decreases through increasing the
O.D. or W.T. of the conductor. Therefore, from the perspective of improving the lateral deformation and deflection angle of the conductor, increasing the O.D. and W.T. of the conductor can significantly improve the stability of the subsea wellhead.

3.3.4. Mechanical Parameters of the Soil

Generally, the subsea soil is silt, silty sandstone, a clay-sand mixed layer, silt or clay, whose stability and diagenetic ability are relatively poor. Therefore, it is of significance to study the influence of the strata lithology on the stability of the subsea wellhead. In this section, the influence of the internal friction angle, cohesion and density on the lateral dynamic bearing capacity of the conductor is discussed. When the cohesion is 30 kpa, the density is 1800 kg/m³, and the internal friction angle changes from 20° to 40°; the lateral dynamic response of the conductor is shown in Figure 16. When the internal friction angle is 20°, the density is 1800 kg/m³ and the cohesion changes from 20 kPa to 40 kPa; the lateral dynamic response of the conductor is shown in Figure 17.

![Figure 16](image1.png)

**Figure 16.** The influence of the internal friction angle on the mechanical response of the conductor, where (a) is the variation of the lateral moment at the top of the conductor with time and (b) is the variation of the bending moment along the conductor axial direction when the internal friction angle is 40°.

![Figure 17](image2.png)

**Figure 17.** The influence of cohesion on the mechanical response of the conductor, where (a) is the variation of the lateral moment at the top of the conductor with time and (b) is the variation of the bending moment along the conductor axial direction when the cohesion is 20 kPa.

As shown in Figure 16, the maximum lateral deformation at the top of the conductor decreases gradually with the internal friction angle. In this case, when the internal friction angle is 20°, 30°, and 40°, the maximum lateral deformation is 0.0499 m, 0.0470 m, and
0.0443 m, respectively. Besides, the lateral deformation along the conductor axial direction decreases with the internal friction angle. However, the influence of the internal friction angle on the maximum bending moment is negligible. As shown in Figure 17, the maximum lateral deformation at the top of the conductor decreases with the increase in the soil cohesion. In this case, when the cohesion is 20 kPa, 30 kPa, and 40 kPa, the maximum lateral deformation is 0.0757 m, 0.0705 m, and 0.0669 m, respectively. The influence strength of the cohesion on the lateral deformation is comparable to that of the internal friction angle. Comparing Figure 16b with Figure 17b, the conclusion can be drawn that both the internal friction angle and the cohesion have a negligible effect on the conductor bending moment. When the cohesion is 20 kPa, the density is 1800 kg/m³, 1900 kg/m³, and 2000 kg/m³, the maximum lateral deformation is 0.0757 m. Therefore, the soil density also has limited influence on the mechanical response of the conductor.

4. Conclusions

(1) The lateral deformation, deflection angle and von Mises stress calculated by the Goodman contact element model are greater than those calculated by the contact surface model. Therefore, we recommend that the Goodman element model should be paid sufficient attention while analyzing the stability of the subsea wellhead during deepwater drilling.

(2) The maximum lateral deformation and bending moment of the conductor decrease with the O.D. and W.T. of the conductor and the cohesion and internal friction angle of the soil, while they increase with the wellhead stick-up. Both the vertical force on the conductor and the soil density have a negligible effect on the lateral response of the conductor.

Nomenclature

\[ c \] = soil cohesion, MPa
\[ c(x) \] = damping coefficient of the soil, N/m·s
\[ c_0 \] = clearance and pressure on the contact surface, m
\[ EI \] = bending stiffness, N·m²
\[ h \] = distance between the two contact surfaces, m
\[ k_n \] = normal stiffness coefficient of the contact surface, N/m²
\[ k_s \] = tangential stiffness coefficient of the contact surface, N/m²
\[ L \] = distance between the two nodes in Goodman element model, m
\[ m \] = mass of the conductor per length, kg/m
\[ N(x) \] = axial force of the conductor, N
\[ p_0 \] = pressure on the contact surface, MPa
\[ t \] = time, s
\[ u_r \] = relative displacement of the contact surface, m
\[ x \] = conductor depth, m
\[ y(x, t) \] = lateral deformation of the conductor, m
\[ a_0 \] = undetermined constant, dimensionless
\[ a_1 \] = undetermined constant, dimensionless
\[ \gamma_s \] = tangential relative displacement of the contact surface, m
\[ \varepsilon_n \] = normal relative displacement of the contact surface, m
\[ \sigma \] = normal stress, MPa
\[ \sigma_n \] = normal stress on the contact surface, MPa
\[ \tau \] = shear strength, MPa
\[ \sigma_r \] = relative stress, MPa
\[ \tau_s \] = tangential stress on the contact surface, MPa
\[ \varphi \] = internal friction angle, °
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References


