The Lateral Load and Levelness Analysis of Subsea Wellhead Based on P-Y Curves Method

Gongxiang Zhong, Yankai Zhang, Weijie Zhang
MOE Key laboratory of Oil & Gas Equipment, Southwest Petroleum University, Chengdu 610500, China

Abstract: A monopole model is designed for the wellhead fixed system which consists of condition and cement loop based on the design specification of architectural foundation and offshore engineering of oil and gas. The p-y curves method and ocean current theory is chosen to analyze the bearing force and the levelness analysis of wellhead is made by a non-linear spring finite elements method to confirm the whole wellhead’s working situation. The previous simulation results are imported in the mud mat model of the template for a further simulation and the results show that the levelness meets the requirement when wellhead system meets the requirements of environmental load. The research and the relevant method can provide a theoretical basis for the design of wellhead and template system.

Keywords: p-y curves; subsea wellhead; levelness; subsea drilling;

1. Introduction
In the field of subsea drilling, the stability of wellhead determines whether the drilling engineering can be proceeded. Thus, the levelness is a key factor and evaluation index of assembling the template with the wellhead in order to avoid the relative equipment’s damage in subsea environment. A way of calculating the levelness of a subsea wellhead system is put forward in the sequel.

The monopole model is chosen for analyzing the condition and cement loop based on the environmental factors such as gravity, current force and ground resisting force. Because of the non-linear of the practical situation, the p-y curves method and Morison equation is chosen for the statics analysis. And a numerical simulation is put forward to quantify the template system based on the checking of pile theory and standard [1][2]

In early subsea drilling process in shallow water, the risers’ lower segments are assembled under the mud-line as the conditions without the subsea wellhead. The
subsea BOP (Blow-out Preventer) and wellhead became necessary during the increasing of water and drilling depth with indefinite and dangerous factors. As the major equipment of well control and safety, the subsea BOP stacks and its reliability is depended on the working state of wellhead and its fixed system [3]. Besides, the wellhead also need to suspend the casings group and separate the pressure between stratum and seawater. And all the functions are depended on the reliability of the condition-cement-loop system (Fig 1 for a brief introduction of wellhead system) [4]

![Fig1. Typical Structure of a Wellhead System](image)

2. The Model of Condition and Cement Loop Based on Pile Theory
Before drilling the stratum, the seabed need to be leveled first by the subsea ROV (Remote Operation Vehicle). Installing the template is the next step. After that, the first segment of condition is installed by jet drilling method and then cement the annular space for fixing the template and the wellhead with it. After the ROV’s checking, the BOP stacks can be assembled on the wellhead by the riser system. During the drilling, the casing also suspended on the wellhead. So, in that process, the weight of subsea BOP stacks, conditions and casings apply the vertical load. The current force on subsea BOP stacks apply the lateral force.
The soil parameter in the paper was chosen from an experiment in South China Sea. It shows in Table 1[5]
Table 1. Soil Parameter of Somewhere in South China Sea

<table>
<thead>
<tr>
<th>Soil Layer</th>
<th>Soil layer Thickness/m</th>
<th>Effective Unit Weight/kNm-3</th>
<th>Internal Friction Angle/°</th>
<th>Un-drained Shear Strength/kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mucky Silty Clay</td>
<td>14.2</td>
<td>8.4</td>
<td>0.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Silty Clay</td>
<td>3.5</td>
<td>8.6</td>
<td>0.0</td>
<td>30.0</td>
</tr>
<tr>
<td>Silty Fine Sand</td>
<td>29.3</td>
<td>10.9</td>
<td>32.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>13.0</td>
<td>10.6</td>
<td>34.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>25.6</td>
<td>10.8</td>
<td>35.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The basic data of subsea wellhead system is showed in Table 2 based on API 17D, Pile Engineering Manual, Design Specification of Architectural Foundation, Classification and Construction Specification of Mobil Offshore Platform and Offshore Engineering of Oil and Gas [6][7][8][9].

Table 2. Basic Data

<table>
<thead>
<tr>
<th>Calculation Parameters</th>
<th>Numerical Value</th>
<th>Calculation Parameters</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Depth/m</td>
<td>500</td>
<td>Elasticity Modulus of Cement Loop/GPa</td>
<td>80</td>
</tr>
<tr>
<td>Wind Current Velocity /ms-1</td>
<td>1.0</td>
<td>Height of SBOP/m</td>
<td>20</td>
</tr>
<tr>
<td>Surface Tidal Velocity/ms-1</td>
<td>1.0</td>
<td>Weight of SBOP/kN</td>
<td>2000</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>1.0</td>
<td>Length of Condition/m</td>
<td>40</td>
</tr>
<tr>
<td>Condition Density/kNm-3</td>
<td>7850</td>
<td>Outer Diameter of Condition/m</td>
<td>0.381</td>
</tr>
<tr>
<td>Cement Loop Density/kNm-3</td>
<td>2500</td>
<td>Inner Diameter of Condition/m</td>
<td>0.350</td>
</tr>
<tr>
<td>Elasticity Modulus of Condition/GPa</td>
<td>210</td>
<td>Outer Diameter of Cement Loop/m</td>
<td>0.487</td>
</tr>
</tbody>
</table>
The pile model used in the wellhead fixed system is submit to a long pile model. The criterion can be written as:

\[ T = \sqrt{\frac{E I}{K b_p}} \]  

(1)

Where \( E \) is the elasticity modulus of pile, \( I \) is the second moment of area, \( b_p \) is the calculative width of pile, \( K \) is the growth ratio of foundation coefficient along the length.

When \( l/T < 2.5 \), the model is submit to a short pile model; when \( 2.5 < l/T < 4 \), the model is submit to a middle pile model; when \( l/T > 4 \), the model is submit to a long pile model.

Based on the above and relative installation and assembly technology, the specifications of monopole model of condition and cement loop are:

1. The pile model is submit to a long pile model;
2. The pile model is a non-squeeze out soil pile;
3. The pile model is a cement grouting pile [10] [11]

### 2.1 The Bearing Capacity Check of Condition and Cement Loop Unit

The bearing capacity of pile tip of monopole model is given by:

\[ q_{pu} = \zeta_c c N_c + \zeta_q \gamma h N_q \]  

(2)

Where \( q_{pu} \) is the bearing capacity of pile tip, \( \zeta_c, \zeta_q \) is the shape coefficient (which can be found in Pile Engineering Manual), \( c \) is the cohesive force of the soil contact to the pile tip, \( \gamma \) is the unit weight of soil, \( N_c, N_q \) is the bearing capacity factor which is relevant to internal friction angle and shape coefficient.

The bearing capacity force of pile side is given by:

\[ q_{su} = \lambda (\gamma + 2C_u) \]  

(3)

Where \( q_{su} \) is the bearing capacity force, \( \lambda \) is the parameter which is relevant to stratum depth, \( C_u \) is the un-drained shear strength of soil, For layered soil, the bearing capacity force of pile side should be calculated in each layer.

The total bearing capacity is given by:

\[ Q_p = A q_{pu} + U \Sigma L_i q_{sui} \]  

(4)

Where \( Q_p \) is the ultimate capacity of pile, \( A \) is the sectional area of pile, \( U \) is the perimeter of pile, \( L_i \) is the thickness of each soil layer, \( q_{sui} \) is the bearing capacity force of each soil layer.

\( Q_p = 7.54 \times 10^6 N \) based on the data from table1 and 2. The safety factor \( k = 3 \) above 2 which is used in common subsea engineering.

### 2.2 The Subsidence Check of Condition and Cement Loop Unit

In the field of subsea pile-soil analysis, the subsidence cannot beyond 60mm for a high levelness demanding structure. For a layered soil, the subsidence is given by:

\[ S = \frac{P}{E_s I_0} R_p \]  

(5)

Where \( S \) is the subsidence, \( P \) is the vertical load, \( E_s \) is the soil modulus of corresponding soil layer, \( I_0 \) is the subsidence coefficient of bearing stratum of pile tip,
$R_b$ is the stiffness corrective coefficient of bearing stratum of pile tip (the value of $I_0$ and $R_b$ can be found in Pile Engineering Manual). The calculation shows the monopile’s subsidence is 26mm, which meets the requirement.

3. The Environmental Load Analysis of Condition and Cement Loop Unit

3.1. The Lateral Load Analysis of Subsea Wellhead System

Obvious lateral load could be applied by current force on subsea BOP stacks which height is up to 20m. The Morison equation is used to calculate the quantity of current force. The ocean current force can be expressed as:

$$f_c = \frac{1}{2} C_D \rho_w D v_c^2$$  \hspace{1cm} (6)

Which $\rho_w$ is the density of seawater, $D$ is the outer diameter of the tubular pile, $C_D$ is the drag coefficient which is relevant to Reynolds number and the surface roughness of BOP stacks. Because of the different and complex surface structure of BOP units and guide frame, the relative surface roughness can beyond 1, thus the drag coefficient is 1.0 (based on relative diagram), the diameter of BOP stacks should increase 20%.

$v_c$ is the most possible flow velocity of the depth of the wellhead which is given by:

$$v_c = v_m (h/H) + v_T (h/H)^{1/7}$$  \hspace{1cm} (7)

Which $v_m$ is the wind current velocity, $v_T$ is the surface tidal velocity, $h$ is the length between calculate depth and water depth (height of BOP stacks), $H$ is the water depth.

3.2 The Analysis of Ground Resisting Force Based on P-Y Curves

The pile model consists of conditions and cement loop which bears all the lateral load from environment. For complex layered soil, a non-linear p-y curves method shows a good result of adaptability and accuracy. An explanation and specification are given in API 17D and Classification and Construction Specification of Mobil Offshore Platform. And, Reese and Naggar and Novak studied the soil resisting force in details [12] [13]. Because all the clay soil’s un-drained shear strength is less than 96kPa, the p-y curves formula can be written as [14]:

$$\begin{align*}
\frac{P}{P_u} &= 0.5 \left( \frac{Y}{Y_{50}} \right)^{3/2}, & \frac{Y}{Y_{50}} < 8 \\
\frac{P}{P_u} &= 1, & \frac{Y}{Y_{50}} \geq 8
\end{align*}$$  \hspace{1cm} (8)

Which P is the horizontal ground resisting force of depth $x$, $P_u$ is the limit force of ground resisting on lateral unit area ($P_u$ is given in equation 9), $Y$ is the horizontal deformation of ground in depth $x$, $Y_{50}$ is the displacement when the resisting force reaches to its half limit.

$$\begin{align*}
P_u &= 3C_u + \gamma x + \frac{V_T}{D}, & 0 \leq x \leq x_R \\
P_u &= 9C_u, & x \geq x_R
\end{align*}$$  \hspace{1cm} (9)
In equation 9, $C_u$ is the un-drained shear strength, $\gamma$ is the unit weight of ground soil, D is the diameter of pile, $x_R$ is the turnover point depth of limit bearing lateral load which is given as:

$$x_R = \frac{6D}{\gamma_D}$$

(10)

The symbols in equation 9 are the same as equation 10.

The p-y curves formula of sand soil in deep layer can be expressed as:

$$P = A P_u \tanh \left( \frac{kx}{A P_u} \right)$$

(11)

Which A is the coefficient which is relevant to alternating load or static load ($A = 0.9$ for alternating load and $A = [3.0 - 0.8(x/D)] \geq 0.9$ for static load), k is the initial modulus which is relevant to inner friction angle based on relative diagram, $P_u$ is the limit force of ground resisting which is given by:

$$P_u = \begin{cases} (C_1x + C_2D)\gamma x, \: x < x_R \\ C_3D\gamma x, \: x \geq x_R \end{cases}$$

(12)

Which $C_1$, $C_2$, $C_3$ is the coefficient which is relevant to inner friction angle $\phi$ based on relative diagram, $x_R$ is the turnover point of limit lateral ground resisting force between shallow soil and deep soil which is given by:

$$x_R = \frac{(C_3 - C_2)D}{C_1}$$

(13)

The symbols in equation 13 are the same as equation 12 and 11.

The value of p-y curves can be given based on above and the parameters of ground soil layer. The result is given in table 2.

Table 3. Data of P-Y curves

<table>
<thead>
<tr>
<th>Depth</th>
<th>Data of P-Y curves (P(N)/y(m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
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<td></td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Which the data in Table 3 can be showed in Fig 2 as a set of curves, a significant variation of ground soil is given.

Fig 2. The Set of P-Y Curves of Ground Soil

4. The FEM Simulation of Pile Model on Vertical and Lateral Load

Based on the acquired data, a simulation analysis can be done by software ANSYS. In the simulation, the condition and cement loop model are used in pile model PIPE16 and PIPE59, the ground resisting force is used in non-linear spring model COMBIN39 (the acquired p-y data can be used as the real constant of COMBIN39 model). The vertical and horizontal load on the model is given in above [15] [16] [17] [18]. The simulation above is showed in Fig 3 and 4.

Fig 3. The Cloud Diagram of Structural Deformation
Based on the calculative results, a conclusion is given:
(1) The biggest structural deformation is up to 0.207m which appears between the pile top and the position under the mud line 5m;
(2) The stress on pile structure is less than its yield stress, the condition and cement loop can work fine in the seawater and ground environment;
(3) The main deformation appears near the mud line which could lead a significant influence to levelness of wellhead system.

5. The Levelness Analysis of Wellhead System in Consideration of Ground and Wellhead Template

Based on above and the cushioning effect from the mud mat of a template, a template model is made and imported in the simulation (a circular mud mat, R=3.0m). The surface ground soil is used in a non-linear elastic plastic model and a connection relation between mud mat and surface ground soil is set. The result of the simulation is given in Fig 4 and 5.
The results show that the biggest displacement on vertical direction is 0.012m, which the levelness is $\theta = \arctan(0.012/1.5)=0.45^\circ$, meets the requirement in offshore engineering of oil and gas about the levelness of wellhead system cannot beyond 0.5°.

6. Conclusion
(1) A method of calculating and analyzing the wellhead levelness is put forward, which considers the system consists of condition and cement loop as a monopole model, and the non-linear influence from vertical and lateral load is considered systematically.
(2) The deformation and displacement are mainly appeared near the mud line, which could lead a significant influence to the levelness.
(3) Only the monopole model of the wellhead fixed system is considered. In actual situation, the fixed process could be functioned by more than one conditions and cement loops, and the model of group piles may be used in that situation [19] [20]
(4) The outer surface of BOP stacks is quite complex which its drag coefficient cannot be confirmed based on the surface roughness in the traditional method, a simulation with coupled current flux and structure or experiment should be made in further research to acquire the accuracy $C_D$.
(5) The environmental load is considered as static force in the analysis, the dynamic load from ocean current force and ocean internal wave on wellhead system remains research [21.22.23.24]

References


