Practical Design Considerations Of Monopile Foundations With Respect To Scour

Yu-Shu Kuo, Martin Achmus
Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering, Leibniz University of Hannover, Germany.
Tel: +495117623370
Email: kuo@igbe.uni-hannover.de; achmus@igbe.uni-hannover.de
Mail Address: Appelstr. 9A, IGBE, D-30167 Hannover, Germany

Chuan-Shen Kao
Registered geotechnical professional engineer, Taiwan, China
Tel: +886425288159 Email: jason@infra-vest.com
Mail Address: 10-2F, No. 9, Sec. 2, Roosevelt Rd., 10094, Taipei, Taiwan Province, China

Abstract:
The emphasis of this study is to evaluate the lateral response of monopile foundation with a scour. A three dimensional finite element model is developed to study the lateral deformation response of pile under monotonic and one-way cyclic loading. The monopile is considered as partly unsupported down to the scour depth. With this model, the lateral deformation of piles with a scour can be quantified. A case study on the planned wind turbine in Taiwan Strait is analyzed, and the economic evaluation of different design options is discussed.

Keywords: offshore wind energy, monopile, scour, cyclic

1. Introduction

Lots of offshore wind farms are planned in Europe as well as in Asia. Most of the existing offshore wind energy converters in Europe are founded on monopiles. A monopile is a steel pipe pile of large diameter which transfers the loads by horizontal bedding stresses into the subsoil. Such a foundation structure placed on a sandy seabed is sensitive to scour. A considerable scour depth may reduce the lateral resistance of the monopile and lead to an excess deformation of the offshore wind energy converters (OWEC). To avoid the loss of serviceability of OWEC due to excess lateral deformation, a scour protection design is suggested by relevant offshore wind turbine design standards [DNV (2004), GL (2005)]. As an alternative method, an additional pile length can be realized to limit the effect of scour on monopiles.

A finite element model is presented to study the behavior of monopiles under monotonic and cyclic loading and the deformation response of a monopile with different scour depths is quantified. The required additional pile length to ensure the deformation within tolerance value and the economic evaluation of the options is discussed with a case study.
2. Literature Review Of The Scour Effects On The Lateral Behavior Of A Cylinder Pile

The assumed scour depth around a cylinder pile has been investigated by many researchers and suggested in the design guide line of OWEC [Sumer & Fredsøe (2001), DNV (2004), GL (2005), Whitehouse et al. (2006)]. The suggested scour depth $S$ is presented as a factor 1.3 to 2.5 times the pile diameter $D$. In the practical design, a scour factor $S/D$ from 1 to 1.5 is usually adopted.

The behavior of laterally-loaded pile regarding to scour is not investigated intensively till now. A sensitivity analysis on the lateral resistance of piles with small diameter under monotonic load is presented by Diamantidis & Arnesen (1986) with p-y curve method. However, the lateral deformation of the piles with respect to scour is not presented.

For a pile with relatively small diameter ($D \leq 3m$), the application of p-y curves method worked satisfactorily in offshore practice over many years and is recommended by American Petroleum Institute (API, 2000). However, the subgrade modulus for the pile with large diameter ($D \geq 5m$) is overestimated by the API method [Lesny at el. (2007)]. For cyclic loading condition, the cyclic p-y curves are derived from the field tests with a maximum number of 200 loading cycles. For the OWECs, the cyclic lateral load due to wind and wave could exceed 10000 cycles. Hence, the p-y curves method is not suitable to estimate the deformation response of monopile foundations of OWEC with a large diameter.

To investigate the lateral deformation response of large-diameter monopile foundations of OWECs, a three dimensional finite element model is presented by [Achmus et al. (2007), Achmus et al. (2008)]. The lateral deformation response of monopiles under monotonic and long-term cyclic load can be quantified with this model. In this study, the lateral behavior of monopiles with different scour depths is estimated with this finite element model.

3. Investigation Of Monopile Under Lateral Loading With Respect To Scour

Due to symmetry of loading condition, the finite element model is designed as a half-cylinder and the monopile is considered as partly unsupported down to the scour depth (Fig. 1). The lateral load $H$ is applied on the monopile at a height $h$ above seabed. The lateral deformation response is presented as the secant rotation angle $\Phi$, which is defined as the ratio of lateral deformation at seabed after scour $y_s$ and the depth of zero pile deflection point.
In the finite element model, the monopile is simulated as elastic material and a contact surface is considered between the pile and soil. The soil is simulated with elasto-plastic material behavior with Mohr-Coulomb failure criterion and a stress-dependent stiffness modulus $E_s$ implemented as follows:

$$E_s = \kappa \sigma_{at} \left( \frac{\sigma_m}{\sigma_{at}} \right)^\lambda$$

(1)

Herein $\sigma_{at}$ is atmospheric stress and $\sigma_m$ is the current mean principal stress in the soil element, $\kappa$ and $\lambda$ are the oedometer soil stiffness parameters.

To consider the soil behavior under cyclic load, the soil stiffness $E_s$ decreases with the number of cycles $N$ by following equation:

$$\frac{E_{sN}}{E_{s1}} = N^{-b_1(X)^b_2}$$

(2)

Here $X$ is the characteristic cyclic stress ratio, which depends on the static failure stress ratio and cyclic stress level, and $b_1, b_2$ are regression parameters determined from cyclic triaxial tests. The finite element model is introduced briefly herein due to page limitations, more information is available in respective references [Achmus et al. (2007), Achmus et al. (2008)].

The soil parameters used in this study are given in Table 1.

<table>
<thead>
<tr>
<th>Soil parameters</th>
<th>Dense sand</th>
<th>Silty sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit buoyant weight $\gamma'$</td>
<td>11.0kN/m³</td>
<td>12.0kN/m³</td>
</tr>
<tr>
<td>Oedometric stiffness parameter $\kappa$</td>
<td>800</td>
<td>250</td>
</tr>
<tr>
<td>Oedometric stiffness parameter $\lambda$</td>
<td>0.55</td>
<td>0.75</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Internal friction angle $\phi'$</td>
<td>37.5°</td>
<td>32.5°</td>
</tr>
<tr>
<td>Dilation angle $\psi$</td>
<td>7.50°</td>
<td>5.0°</td>
</tr>
<tr>
<td>Cohesion $c'$</td>
<td>0.1kN/m²</td>
<td>0.1kN/m²</td>
</tr>
<tr>
<td>Stiffness degradation parameter $b_1$</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Stiffness degradation parameter $b_2$</td>
<td>5.76</td>
<td>5.0</td>
</tr>
</tbody>
</table>
The rotation responses of a monopile foundation with length $L=30\text{m}$, diameter $D=5\text{m}$ and wall thickness $t=0.06\text{m}$ are presented in Fig. 2. The scour around the pile results in loss of lateral resistance of piles and induces an additional moment $H*S$ on the piles. The rotation angle $\Phi$ increases with lateral load level $H$ for each scour factor $S/D$ under monotonic lateral load.

![Fig. 2 Rotation response of a monopile under monotonic load](image)

Under cyclic lateral loading condition, the deflection of the monopiles under a lateral load $H=2.5\text{MN}$, $h=30\text{m}$ with a scour factor $S/D=1.5$ is presented in Fig. 3. The accumulation rate of lateral deformation after $N$ cycle $y_{SN}/y_{S1}$ and the accumulation rate of rotation angle $\Phi_N/\Phi_1$ increase with the number of cycles $N$ (Fig. 4). For a monopile with a large diameter, a large scour may lead to a significant accumulation of lateral deformation under cyclic load.

![Fig. 3 Deflection of monopile under cyclic load](image)
Fig. 4  Accumulation rate of deformation and rotation of monopiles with respect to scour.

4. Case Study For The Required Embedded Length For Monopile Foundation With Respect To Scour

Several offshore wind farms are planned in Taiwan. The offshore wind farm near Chang Bin industrial zone in Fig. 5 is one of them with highest development potential. The OWECs with capacity 5MW are planned with monopile foundation embedded in silty sand. The total capacity of the wind farm is about 200MW. In this section, a case study on the lateral behavior of monopile with respect to scour at the planned wind farm is analyzed. The economical evaluations of a monopile with scour protection and an additional design pile length are presented.

Fig. 5  The planned offshore wind farm in Taiwan Strait

Based on the limited information, an allowable secant rotation angle of 0.5° is assumed for a monopile with L= 25 m, D=5 m in this case study. The design scour depth is given as 5m, i.e., S/D=1. The extreme loading condition is assumed as H=4MN with a moment arm h=40m and the cyclic fatigue load is assumed as H=2MN with a moment arm h=30m applied on the monopile with 100 cycles. The soil parameters for silty sand are given in Table 1.

The deformation response of the monopile at the planned offshore wind farm is presented in Fig. 6. Under the cyclic fatigue loading, the secant rotation of a monopile with a scour depth is still within the tolerance
value. However, under the extreme loading, the lateral displacement of the monopile with a scour depth increases about 2 times compared to the monopile without a scour. The secant rotation angle of the monopile with a scour is 0.6° and exceeds the suggested tolerance value.

To ensure the serviceability of the OWEC, a scour protection or an additional design pile length is required. When a set of concrete-block scour protection is considered, the seabed level is unchanged and there is no loss of the lateral resistance of the monopile and the additional lateral deformation. If an additional design pile length ΔL=2.5m is considered for a scour depth S=5m, the rotation angle of the monopile under extreme loading (Φ= 0.43°) can be controlled under the tolerance value (Fig. 6).

If only the material cost and the construction fees are considered in the economic evaluation, the cost of scour protection is about three times of the cost of an additional pile length of 2.5m. Under the assumed loading condition, an additional embedded pile length is suggested for the OWEC against scour in Chang Bin industrial zone. In this case study, only estimated design parameters for soil and loading condition were used. For practical design, a detail analysis based on recent information obtained from soil investigations and metrological monitor program is needed.

5. Conclusion

The effect of scour on lateral deformation of the monopile foundations is investigated with a finite element model. The lateral displacement and rotation of the large-diameter monopile under monotonic and cyclic loading are affected significantly by scour. To ensure the serviceability of wind energy converters, an additional pile length can be considered as an alternative method to the scour protection. In the case study for the planned offshore wind farm in Taiwan Strait, an additional pile length is suggested based on
economic assessment.

6. References


