Analysis of Offshore Rock Socketed Monopile Foundations

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ABSTRACT: There are a number of offshore wind farms where the monopile is socketed into rock layers. Since it is socketed into rock, it may behave different from monopile embedded in soil. A numerical modelling of rock socketed monopile is done using finite element (FE) software Abaqus. A stiffness degradation method (SDM) is applied to FE model in order to predict the behaviour under cyclic loading conditions. Parametric studies are carried out by varying rock socketed depth (d), length of monopile below seabed (L), intensity of horizontal loading (H) and subsoil conditions to evaluate the long-term permanent deformation of offshore rock socketed monopile foundations. It is observed from the results that the deformation behaviour of the monopile changes from stiff to flexible with increase in rock socketing and in turn the pile head deflection going down.

Keywords: cyclic loading; rock socketed monopiles; stiffness degradation method; numerical modelling; lateral deformation.

1. Introduction
Monopiles are one of the common foundation options for offshore wind turbines. Often the sea bed is made up of bed rock and rock socketing becomes necessary for installing the monopiles. In many places, the monopiles are being successfully socketed into rock for different wind farms, e.g., situated on the East coast of England in Northumberland, Blyth offshore wind project installed monopiles of diameter 3.5 m into bedrock of sandstone. At North Hoyle wind farm, installation of monopile (4.0 m diameter at seabed) consists of driving through upper layers of sand and clay, and drilling and driving through rock layer of sandstone and mudstone. In Bockstigen wind farm in Sweden monopiles were socketed into rock (www.offshorecenter.dk, www.subacoustech.com, www.technology.stfc.ac.uk). Germanische Lloyd (GL) rules and regulations give the design procedure for foundations of offshore wind energy converters in Germany (Achmus 2010). In this regulation the p-y method defined by API code is recommended in order to estimate the behaviour of piles under horizontal loading. But the use of p-y curves in estimating the behaviour of monopiles may be misleading because of the fact that these curves are formulated based on field testing of piles with number of cycles less than 200 and applicable for piles with diameters up to 2 m.

Many studies have been conducted in the past in order to understand the behaviour of laterally loaded and axially loaded monopiles (Achmus et al. 2009, 2008, Albiker and Achmus 2012, Achmus and Albiker 2014, Arshi and Stone 2011, Kellezi and Hansen 2003, Little and Briand 1988, Schmoor and Achmus 2013) and some design guide lines are also available in the literature (Achmus et al. 2008, Schmoor and Achmus 2013 and Thieken et al. 2014). But the rock-monopile interaction under cyclic loading is less discussed. Arshi and Stone (2011) conducted a series of small scale single gravity tests to investigate the performance of a monopile, combined monopile and bearing plate foundation where the pile is socketed into a weak rock. In the model studies, the weak rock layer is modelled using a weak sand and gypsum mix. The results of the study provide an insight into the effect of the various foundation elements (i.e. pile, plate and rock socket) and their contribution to the overall performance of the foundation system. Wang et. al. (2007) discusses the behaviour of large-diameter rock-socketed CFST (concrete-filled steel tube) piles under lateral loads based on field tests and numerical analysis. The horizontal capacity and deformation of large-diameter rock-socketed piles are analyzed from the measured displacements and internal forces of piles. The interactive behaviour of pile-rock and the influence of backfilled sand on horizontal capacity are also discussed. Using the Finite Element Method (FEM) considering the properties of the pile-soil interface, the test results are simulated numerically. This result show that stress concentration effect in the region near the bottom of the steel tube should be considered in the design, because the socketed part of piles bears most of the lateral load.

From the literature review, it may be concluded that the offshore monopile foundations are mainly subjected to wave and wind loading and these loads are cyclic in nature. One of most important aspects of designing a monopile foundation is the deformation under cyclic horizontal loading and accumulation of permanent deformation with increasing number of cycles. In this paper, the deformation behaviour of rock socketed monopile foundation under cyclic loading is studied by numerical modelling of the pile-soil system using the FEM software Abaqus and by applying the stiffness degradation method (SDM) with increasing number of load cycles. Permanent deformation of the piles under cyclic loading is investigated for different rock socketing depths, different pile lengths and horizontal load magnitudes.

1.1 Stiffness degradation method
This method was developed at the Institute for Geotechnical Engineering, Leibniz University of Hannover, Germany (Achmus et al. 2009). In a cyclic triaxial test, the degraded stiffness of soil after N cycles...
of the soil varies with depth according to the following
\[ \frac{E_{S,N}}{E_{S,1}} = N^{-b_2}X^{b_2} \]
Here \( b_1 \) and \( b_2 \) are soil parameters and \( X \) is the cyclic stress ratio defined by
\[ X = \frac{\sigma_{1,cyclic}}{\sigma_{1,f}} \]
where \( \sigma_{1,cyclic} \) is the maximum principal stress in a cycle and \( \sigma_{1,f} \) is the maximum principal stress at failure subjected to static loading. From cyclic triaxial test results documented in the literature, typical regression parameters \( b_1 \) and \( b_2 \) were found for dense sand to be \( b_1 = 0.12, b_2 = 0.50 \) and for medium dense sand \( b_1 = 0.15, b_2 = 0.50 \). Detailed numerical implementation of the SDM in the finite element code Abaqus (Abaqus documentation version 6.11-3) is discussed in Achmus et al. (2008).

2. Numerical Modelling
The model considered in the present work consists of a monopile of diameter 7.5 m and wall thickness of 9 cm. For simplicity the hollow cylindrical steel monopile (modulus of elasticity \( E = 210 \text{ GPa} \) and Poisson’s ratio \( \nu = 0.2 \)) is replaced by a solid cylindrical pile with same diameter such that bending stiffness of both piles remains the same. The monopile is installed into a layered soil with upper sand and lower rock layer as shown in Figures 1 and 2. The sand is considered elasto-plastic with Mohr-Coulomb failure criterion. The stiffness modulus of the soil varies with depth according to the following equation,
\[ E_s = k \sigma_d \left( \frac{\sigma_m}{\sigma_a} \right)^\lambda \]
Here \( E_s \) is the oedometric stiffness modulus which varies with stress condition, \( \sigma_m \) is the current mean principal stress in the considered soil element and \( \sigma_a = 100 \text{ kN/m}^2 \) is a reference (atmospheric) stress. The parameter \( k \) determines the soil stiffness at the reference stress state and the parameter \( \lambda \) rules the stress dependency of the soil stiffness. The material parameters used to model different materials are listed in Table 1 (Jaeger et al. 2009, Achmus et al. 2009).

![Fig. 1 Schematic sketch showing the subsoil conditions](image)
Fig. 1 Schematic sketch showing the subsoil conditions

The vertical load (\( V \)) acting on the monopile is assumed as 10 MN which is the weight of the superstructure. The variable horizontal load (\( H \)) is acting at a height (20 m) above the seabed level. Three different horizontal load magnitudes are assumed- 10 MN, 15 MN and 30 MN. Due to symmetry conditions, only the half of the pile-soil-model is considered. The diameter of the numerical model considered for analysis is sixteen times the pile diameter. The bottom boundary of the model is extended to 20 m below the base of the monopile.

![Fig. 2 Finite element model using Abaqus/CAE](image)
Fig. 2 Finite element model using Abaqus/CAE

### Table 1. Properties of Materials

<table>
<thead>
<tr>
<th>Soil type</th>
<th>( E_s ) (kN/m²)</th>
<th>( \kappa )</th>
<th>( \lambda )</th>
<th>( \phi’ )</th>
<th>( \psi )</th>
<th>( c ) (kPa)</th>
<th>( \nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense sand</td>
<td>11</td>
<td>700</td>
<td>0.55</td>
<td>37.5</td>
<td>7.5</td>
<td>0.1</td>
<td>0.25</td>
</tr>
<tr>
<td>Hard rock</td>
<td>14</td>
<td>( E = 70 \text{ GPa} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Soft rock</td>
<td>12</td>
<td>( E = 1.0 \text{ GPa} )</td>
<td>25</td>
<td>0</td>
<td>50</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Medium dense sand</td>
<td>11</td>
<td>550</td>
<td>0.6</td>
<td>35</td>
<td>5</td>
<td>0.1</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Table 2. Model conditions in parameter study

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>( V ) (MN)</th>
<th>( H ) (MN)</th>
<th>( L ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>10, 15, 30</td>
<td>30, 40</td>
</tr>
<tr>
<td>Pile geometry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( D ) (m)</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( d ) (m)</td>
<td>0, 2, 4, 6, 8, 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( h ) (m)</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( k/L )</td>
<td>0.09</td>
<td></td>
<td>0.5, 0.67</td>
</tr>
</tbody>
</table>

3. Results and Discussions

3.1 Effect of increase in rock socketing depth

Figure 3 shows the lateral deflection of the pile with depth below seabed for different rock socketing depths (\( d \)- 2 m, 4 m and 10 m and for different number of loading cycles (\( N \))- 1, 10, 100, 1000 and 10000. From
this Figure, it can be seen that with increased rock socketing of the pile, the deflection line of the pile reduces. Moreover, with increased rock socketing, the effect of loading cycle on the deflection response reduces. This is caused by the fact that the pile with zero socketing in the rock behaves like a stiff pile and with increased rock socketing, the behaviour gradually changes from stiff to flexible.

When a stiff pile is subjected to cyclic loading, the degradation of stiffness modulus of the surrounding soil after N number of cycles ($E_N$) occurs throughout the whole embedded length of the pile, while in case of a flexible pile the soil mobilization and degradation occur only in the upper layers, because in the rock socket, the pile is scarcely deformed, as it is noticed from the deflection lines shown in Figure 4. This issue leads to a higher overall soil degradation and thus a higher cyclic deformation accumulation of a stiff pile compared to a flexible pile (Albiker and Achmus 2012). Based on the previous results, the deflection lines after different numbers of cycles for piles lie closer to each other with increased rock socketing, which means that deformation accumulation is decreasing as presented in Figure 3.

The horizontal loading is relatively high (30 MN) with respect to the ultimate horizontal pile capacity, the soil is nearly in the failure state, which in turn leads to an apparently increased pile-soil system stiffness (stiffer behaviour) and therewith to a higher cyclic deformation accumulation as seen in Figure 5.

When a pile is subjected to cyclic loading, the effect of loading cycle on the deflection response reduces. Moreover, with increased rock socketing, the deflection line of the pile nearly in the failure state, which in turn leads to an apparently increased pile-soil system stiffness (stiffer behaviour) and therewith to a higher cyclic deformation accumulation as seen in Figure 5.

3.3 Effect of rock properties on the deformation behaviour

Figure 6 shows lateral deflection of pile for different numbers of loading cycles and socketed in soft and hard rock. From the numerical results, it can be seen that a monopile socketed in hard rock behaves more flexible than that socketed in weak rock, and the accumulation of head deformation for monopiles in weak rock is large compared to the other case (about 4 times larger for 4 m rock socketed piles and 6 times larger for 10 m rock socketed pile). In analogy to the statement given above when different load levels were analysed, also here it can be concluded that a higher stiffness of the rock leads to a reduced pile-soil system stiffness (flexible behaviour) and therewith to a reduced cyclic deformation accumulation.

Figure 7 presents the normalized pile lateral deflection $y_N/y_{s1}$ for different rock socketing depths in soft and hard rock after increasing number of cycles. As the rock socketed depth increases, the rate of accumulation under cyclic loading reduces.

4. Conclusions

The behaviour of laterally loaded piles for varying geometry, soil conditions, lateral loading and rock socketing depths is analysed and studied numerically. From the results it can be concluded that the behaviour of the monopile changes from stiff to flexible with increase in rock socketed depth and that in turn the deformation accumulation of the pile at the surface is going down. The other observation is that accumulation rate of deflections follow the same trend. As the depth of the pile below seabed level increases, rock socketing depth has no significant effect on the accumulation of deformation at low load levels.
5. Acknowledgement

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References


