Centrifuge modelling of mono-pile under cyclic lateral loads

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ABSTRACT: Mono-pile foundations are widely used for wind turbines at present. They are always subjected to significant cyclic lateral loads due to wind and wave actions. In order to better understand the performance of mono-piles under cyclic lateral loads, a series of cyclic lateral load tests was conducted on a stainless steel mono-pile in the centrifuge. The axial and lateral responses of a large diameter mono-pile under one-way force-controlled cyclic lateral loads are described. Accumulated permanent pile shaft lateral displacements caused by cyclic lateral loads are discussed, and a function is utilized to estimate these permanent displacements. Also the influence of cyclic lateral loads on the pile lateral secant stiffness is investigated. These results offer an insight to further research to optimise designs of mono-pile foundations to resist live loads in service.

1 INTRODUCTION

Mono-piles are prevalently used as foundations of wind turbines and other structures. Figure 1 shows a picture of the Danish offshore wind farm Horns Rev 2 in the North Sea. They are designed with the intention of resisting cyclic lateral loads due to wind and wave actions. In order to better protect wind turbine structures, the performance of mono-piles under cyclic lateral loads need to be investigated in greater depth (Ooi et al. 2004).

The cyclic lateral loads mentioned above can influence aspects of the pile behaviour, including pile head displacements, pile secant stiffnesses, p-y curves, and so forth (Verdure et al. 2003). The characteristics of the cyclic lateral load include the cycle numbers, the cyclic load ratio (minimum load /maximum load in a cycle), and the maximum magnitude of load.

Reese & Matlock (1956) developed a method to consider the effect of cyclic loads. It is based upon a closed-form solution for a beam on an elastic foundation with a linearly increasing soil reaction modulus (LISM) that changes proportionally with depth. The LISM method provides a simple procedure for predicting the effect of cyclic lateral loads; however, it cannot explicitly account for effects of nonlinear soil response.

According to field test results of instrumented piles subjected to cyclic loads, Reese et al. (1974) developed a semi-empirical, nonlinear p-y (soil resistance-pile deflection) approach, in which degradation factors obtained empirically are used to predict cyclic p-y relationships based upon degraded static p-y curves. Additionally, O’Neill et al. (1982) suggested to generate cyclic p-y curves by reducing the static soil resistance, p, for a given deflection, y. In both approaches mentioned above, the cyclic p-y curves are independent of the number of cycles. Furthermore, Matlock et al. (1978) used a discrete element model to predict each p-y curve for the complete load history for every load cycle. However, parameters required in this sophisticated approach are difficult to obtain from site characterization studies. Based on previous test data, Long & Vanneste

Figure 1. The Danish offshore wind farm Horns Rev2 in the North Sea.
(1994) improved the p-y approach to consider the effect of the number of cycles. Nevertheless, only 50 or less cycles of lateral loads are executed in most of the tests considered. Moreover, the use of p-y curves often fails to account for the permanent deformation that accumulates with increasing cycles (Moss et al. 1998).

Therefore, additional cyclic load tests need to be conducted with many more cycles than previously to better understand the influence of cycle numbers. Not only the largest pile deflection in each cycle, but also the accumulated permanent displacement and secant stiffness of the pile should be investigated.

In field tests, it is difficult to exert cyclic loading on mono-piles with large diameters due to the limitations of test facilities and high costs. However, centrifuge modelling offers an effective way to understand the influence of cyclic loads on piled foundations. Compared with field tests, centrifuge tests are more convenient, efficient and cheaper.

In this research, a series of cyclic lateral load tests were conducted in the centrifuge. The axial and lateral response of a large diameter mono-pile under one-way force-controlled cyclic lateral loads is described. The accumulated permanent pile shaft lateral displacements caused by cyclic lateral loads are discussed, and a function is utilized to estimate these permanent lateral displacements. Also, the influence of cyclic lateral loads on the pile lateral secant stiffness is investigated.

2 EXPERIMENTAL METHODOLOGY

2.1 Acceleration and scaling in centrifuge tests

A centrifuge test on a 1/100 scale mono-pile is proposed to be conducted in saturated sand at 100g to model the behaviour of mono-pile foundations for offshore wind turbines. In saturated sand, the effective vertical stress of soil is expressed in the following equation 1:

$$\sigma'_v = \rho'_sG_{sat}z$$  

where $G_{sat}$ is the acceleration in a centrifuge test in saturated sand, i.e. $G_{sat} = 100$ g; $\rho'_s$ = the buoyant density of saturated soil (1137 kg/m³); and $z$ = the depth of soil in a 1/100 scale model.

For the purpose of an initial study, the fully drained cyclic response was required. Since excess pore pressures were to be avoided, it was realised that dry sand could conveniently be used. In order to achieve the equivalent soil conditions, the vertical stress of dry sand expressed in equation 2 should be equal to the effective vertical stress of saturated sand in equation 1:

$$\sigma_v = \rho_dG_dz$$  

where $G_d$ is the acceleration to be imposed in a centrifuge test on dry sand; $\rho_d$ = the dry density of the sand (1826.5 kg/m³); and $z$ = the depth of soil in a 1/100 scale model. Thus the $G_d$ value is 62.3 g, obtained by equation 3:

$$G_d = \frac{\rho'_s}{\rho_d}G_{sat} = 62.3g$$  

(3)

2.2 Test apparatus

Mono-pile tests were conducted in the Turner beam centrifuge at the Schofield Centre, Cambridge University. A new servo actuator was used to apply force-controlled cyclic lateral loads to the mono-pile, as shown in Figure 2. The design of the actuator and an introduction to the facility can be found in Haigh et al. (2010).

2.3 Model pile

A stainless steel tubular pile was used, with an outer diameter of 50 mm and an internal diameter of 42 mm. The embedment depth and total length of the pile were 250 mm and 972 mm respectively. The application of lateral load so high above the soil surface was taken to represent the typical proportions of an offshore pile foundation. The pile tip is flat and open-ended. The shaft surface is smooth, and the pile head is free to rotate (i.e. pinned). A load cell is mounted on the pile head to measure lateral loads, as shown in Figure 2.

2.4 Instrumentation

Pile head axial displacements were measured by a Linearly Variable Differential Transformer (LVDT) mounted on the actuator, with a maximum stroke length of 22 mm. Additionally, pile shaft lateral dis-
placements at levels of 120 mm and 210 mm above the sand surface respectively were measured using two lasers, as shown in Figure 3. Thus, the pile deflection and rotation angle at any level above the sand surface can be deduced using the elastic beam deflection formula.

![Figure 3](image_url)

**Figure 3. The elevation view of the test package**

### 2.5 Sand and container

Dry Wunder sand was used in this project, with $d_{50}$ of 0.52 mm. Since the ratio of pile diameter to average grain size was about 100, and larger than the limiting value of 20 suggested by Gui et al. (1998), the sand should have behaved like a continuum as would be the case in the prototype. The sand was pluviated into a cylindrical steel container (850 mm diameter and 400 mm deep) by an automatic sand-pouring machine (Madabhushi et al. 2006). A dense homogeneous sand specimen with a relative density of 97% was achieved. The cylindrical model container was designed to be strong enough to sustain the large soil pressure in centrifuge tests, and the test location was in the centre of the container ($D_{\text{container}}/D_{\text{pile}} = 17$). Since the focus of this work is lateral loading, the pile was to be jacked in place at 1 g, and no extra vertical load was to be applied at the pile head when testing at 62.3 g, there was no need to be concerned over the relatively small 50 mm sand gap which was left between the base of the pile and the floor of the container.

### 3 TEST RESULTS

#### 3.1 Load-displacement response

In this research, the mono-pile head was pinned, with no applied axial load or bending moment. One-way force-controlled cyclic lateral loads were conducted on the pile head. All the information on these cyclic lateral load tests is listed in Table 1. It should be noted that test ZL06-1 was conducted in one flight, while tests ZL06-2, 3, and 4 were conducted successively in another flight, keeping the pile in its existing location.

<table>
<thead>
<tr>
<th>Test</th>
<th>Min. Force</th>
<th>Max. Force</th>
<th>Frequency</th>
<th>Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZL06-1</td>
<td>0</td>
<td>206</td>
<td>0.02–0.7</td>
<td>174</td>
</tr>
<tr>
<td>ZL06-2</td>
<td>0</td>
<td>411</td>
<td>0.08–0.4</td>
<td>1000</td>
</tr>
<tr>
<td>ZL06-3</td>
<td>0</td>
<td>620</td>
<td>0.06–0.3</td>
<td>160</td>
</tr>
<tr>
<td>ZL06-4</td>
<td>0</td>
<td>810</td>
<td>0.25</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 4 presents the axial displacement history of the pile subjected to cyclic lateral loads with an amplitude of 411 N in test ZL06-2. Although the lateral deflection of the pile induces some pile head axial displacement attributed to the geometric relationship, the cyclic lateral loads do not induce obvious pile head settlement within 1000 cycles.

![Figure 4](image_url)

**Figure 4. Pile head axial displacement variation during cyclic lateral load tests.**

Figure 5 presents lateral force-displacement curves of the mono-pile under one-way cyclic lateral loads with different amplitudes. Lateral displacements of the pile used here were measured at a point 210 mm above sand surface. In test ZL06-1 over virgin sand, the loading curve in the first cycle exhibits evident nonlinearity of soil, with the gradient reducing with increasing lateral displacement. In the following cycles, the unloading and reloading curves are relatively linear and stiffer than the first cycle, as shown in Figure 5(a).

The final unloading in ZL06-1 from ~200 to 0 N created a recoil of ~0.5 mm prior to stopping the centrifuge. When ZL06-2 was carried out at 62.3 g the next day, it may be seen in Figure 5(b) that the first reloading induced ~0.5 mm lateral displacement at ~200 N, confirming that the centrifuge stop-start cycle had no influence on the results. However, lat-
eral cycles with amplitude ~400 N can be seen to
created the same sort of response as in

ZL06-1 with the soil-pile reaction becoming stiffer,
with an increasing permanent displacement. Each
time the lateral load amplitude was increased, in
ZL06-3 and then in ZL06-4, the same phenomenon
occurred but with very much reduced ‘first cycle
gen. Each time the load was increased, the first
part of the reloading curve correctly reproduced the
previous unloading behaviour.

3.2 Minimum and maximum pile lateral

displacements

Pile lateral force-displacement curves are seen in
Figure 5 to keep moving forwards under cyclic lat-
eral loads, the minimum displacement (also known
as accumulated permanent displacement) and the
maximum displacement of the pile both increase
with the increasing number of load cycles, indicating
that significant permanent deformation of the soil
develops around the pile shaft, caused by cyclic lat-
eral loads. With one-way cyclic shearing, the in-
duced lateral soil stress states will be ‘large’ at
maximum displacement and ‘small’ at the end of the
return leg. This lack of symmetry is thought to lead
to the local densification of the sand in front of the
pile, thus creating the progressive pile lateral perma-
nent displacement.

Under cyclic lateral loads with amplitudes
smaller than 810 N, the minimum and maximum pile
lateral displacements in each cycle increase ap-
proximately linearly with the increasing number of
cycles on a logarithmic scale, as shown in Figure 6.
This relationship can be expressed by equation 4
(Verdure et al. 2003):

\[
y_N = y_1(1 + C_N \ln N)
\]

where \(y_1\) is the minimum or the maximum pile lat-
eral displacement at the first cycle; \(C_N\) is the growth
rate of displacement; \(N\) is the number of cycles; and
\(y_N\) is the minimum or maximum displacement in the
\(N^{th}\) cycle.

\(C_N\) values for the minimum and maximum dis-
placements in cyclic load tests are listed in Table 2.
It is evident that \(C_N\) rises with the increasing ampi-
tude of cyclic lateral loads. This is because cyclic
lateral loads with larger amplitude lead to more serious cyclic shearing of the sand surrounding the pile shaft, thus inducing larger permanent pile lateral displacements in each cycle.

Table 2. $C_N$ values for different cyclic lateral load tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Load amplitude</th>
<th>Displacement type</th>
<th>$C_N$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZL06-1</td>
<td>206</td>
<td>Minimum displacement</td>
<td>0.52</td>
</tr>
<tr>
<td>ZL06-2</td>
<td>411</td>
<td>Minimum displacement</td>
<td>0.73</td>
</tr>
<tr>
<td>ZL06-3</td>
<td>620</td>
<td>Minimum displacement</td>
<td>1.20*</td>
</tr>
<tr>
<td>ZL06-1</td>
<td>206</td>
<td>Maximum displacement</td>
<td>0.17</td>
</tr>
<tr>
<td>ZL06-2</td>
<td>411</td>
<td>Maximum displacement</td>
<td>0.23</td>
</tr>
<tr>
<td>ZL06-3</td>
<td>620</td>
<td>Maximum displacement</td>
<td>0.25*</td>
</tr>
</tbody>
</table>

* $C_N$ is calculated from the first 12 cycles in test ZL06-3.

When the amplitude of cyclic lateral load reaches 810 N, $C_N$ increases with the increasing number of cycles instead of keeping constant. It indicates that pile lateral displacements will no longer converge at some critical value if the load cycle continues; and the pile will develop excessive lateral deflections after a certain number of cycles.

3.3 Pile secant lateral cyclic stiffness

The pile lateral secant cyclic stiffness ($K_{s,i}$) is defined here as the ratio of the lateral load to the pile shaft lateral displacement at a level of 210 mm above the sand surface. In test ZL06-1 and 2, $K_{s,1}$ in the first cycle is much smaller than those in subsequent cycles, caused by the high non-linearity of the virgin lateral force-displacement curve as mentioned before. After a dramatic increase in the first cycle, $K_{s,i}$ increases slightly with the increasing number of load cycles but at a reducing rate, as shown in Figure 7 (a). In test ZL06-3, the non-linearity of loading curve in the first cycle is no longer evident due to the soil stress history induced in the preceding test, and $K_{s,i}$ increases gradually from the first cycle. In test ZL06-4, $K_{s,i}$ keeps almost constant when the load amplitude increased to 810 N. Independent of load amplitude, it seems that the largest value of $K_{s,i}$ in all tests is about 470 N/mm after cyclic loading.

To minimize the influence of nonlinear behaviour of soil from the virgin state, the normalised cyclic secant stiffness of virgin soil is defined in terms of the second cycle of load. $K_{s,i}$ is divided by $K_{s,2}$ in the second cycle for test ZL06-1 and 2; while $K_{s,i}$ is divided by $K_{s,1}$ in the first cycle for test ZL06-3 and 4, as shown in Figure 7(b). It is evident that the normalised stiffness increases by approximately 18% within 100 load cycles with amplitudes smaller than 810 N. The local densification of soil attributed to lateral cycling might raise the shear modulus of the sand around the pile and lead the pile secant stiffness to increase with the increasing number of load cycles.

In the cyclic load test with an amplitude of 620 N, the maximum lateral load in the 13th cycle was much larger than 620 N due to a fault in the load-control operation. Therefore, a remarkable permanent pile lateral displacement developed in the 13th cycle, and the gradient of the displacement variation increased significantly after that cycle.
4 CONCLUSIONS

A series of force-controlled one-way cyclic lateral load tests was conducted on a model of a large diameter mono-pile in the centrifuge.

The cyclic lateral loads do not induce evident pile head settlement within 1000 cycles.

The force-controlled one-way cyclic lateral loads induce significant accumulated permanent pile lateral displacements. These displacements might be caused by the local densification of sand around the pile shaft.

When the amplitude of cyclic lateral loads is smaller than 810 N, the minimum displacement (accumulated permanent displacement) and the maximum displacement of the pile increase approximately linearly with the logarithm of the number of cycles, and they can be expressed by an equation: \( y_N = y_1 (1 + C_N \ln N) \). The incremental rate of lateral displacement \( C_N \) increases with the increasing amplitude of cyclic loads. This is because cyclic lateral loads with larger amplitude lead to more significant local densification of sand surrounding the pile.

When the load amplitude reaches 810 N, \( C_N \) increases with the increasing number of cycles instead of keeping constant, indicating that the pile will suffer an excessive deflection if the load cycles continue.

Apart from a dramatic increase in the pile lateral secant cyclic stiffness (\( K_s \)) in the first cycle, \( K_s \) increases slightly with the increasing number of load cycles but at a reducing rate when the load amplitude is smaller than 810 N. It is possible that the local densification of sand around the pile increases the soil stiffness and therefore the pile lateral secant stiffness. The \( K_s \) value rises by around 18% within 100 cycles, and the largest value of \( K_s \) is about 470 N/mm, unrelated to the load amplitude.

These results offer an insight to further research to optimise the design of mono-pile foundations for wind turbines subjected to cyclic lateral loads caused by wind and wave actions in service.

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REFERENCES


