Piled-cruciform attachment to monopile head reduces deflection

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Much critical infrastructure, including bridges, wind turbine structures, dolphins and some other ocean engineering structures, is supported on large-diameter rigid monopiles. For such structures, compared with the gravitational loads, cyclic lateral loading may often be more critical for the analysis and design. The lateral load-carrying capacity of a pile depends on its geometry (dimensions), the soil properties and type of loading. In order to increase its lateral load-carrying capacity, it is necessary either to change the properties of the near-surface layers of soil or to change its geometry. This paper presents model studies investigating a novel technique to limit the lateral deflection (rotation) of a monopile under long-term cyclic lateral loading. The technique provides enhanced restraint of the monopile through the installation of four shorter piles, arranged in a cruciform, which attach to the head of the central monopile by way of a grillage. Different aspects of this modification, including its fabrication and attachment to the monopile, are presented. Its efficiency in reducing the monopile rotation under cyclic lateral loading is evaluated through a comprehensive testing programme, with reasonably encouraging results.

Notation

- $a$: monopile rotation
- $b$: rotation of monopile with piled-cruciform attachment in situ
- $D$: outer diameter of pile
- $d_{10}$: effective grain size for 10% passing by mass
- $d_{30}$: effective grain size for 30% passing by mass
- $d_{60}$: mean effective grain size
- $d_{80}$: effective grain size for 60% passing by mass
- $E_I$: bending stiffness
- $k_s$: initial coefficient of subgrade reaction
- $L$: monopile embedment length
- $L_{SDP}$: embedment length of small diameter pile
- $P_a$: ultimate static lateral load-carrying capacity
- $\eta L$: dimensionless embedment length of monopile

1. Introduction

The preferred foundation solution for a particular offshore structure depends, among other factors, on the local soil conditions, water depth, anticipated loading and financial constraints (Malhotra, 2010). Large-diameter monopiles are a frequently used foundation system for offshore wind turbines and other offshore structures. Offshore wind farms often contain can comprise many hundreds of turbines supported at heights of typically 30–80 m above mean sea level. The preferred foundation type for these tall structures in water depths of up to 30 m is large-diameter monopiles, owing to their ease of construction and installation. These monopiles are subjected to large cyclic lateral and moment loads, in addition to axial loads, as documented by LeBlanc et al. (2010), Bhattacharya et al. (2011) and Cuellar (2011). However, their lateral load-carrying resistance may not be sufficient to withstand prolonged impact under large wind and wave loading. A solution may be achieved by simply increasing the physical dimensions of the monopile, but this may not be economically or practically feasible. Thus, a range of different foundation solutions in place of, or modifications of, the monopile are being investigated by different researchers.
Modification of the conventional monopile by the attachment of 'wings' close to the pilehead, in order to increase the lateral load-carrying capacity and stiffness of the foundation system for weaker soil conditions (closer to the mudline), has been investigated by many researchers using small-scale tests in sand under the normal gravitational (1g) condition (Dührkop and Grabe, 2008; Nass, 2014; Peng et al., 2011) and in centrifuge facilities (Bienen et al., 2012). These researchers found that, with the wings attached, the pilehead deflection substantially reduced (by ~50–70%) and the ultimate lateral load-carrying capacity increased by up to 80%, depending on the length of the wings compared with the length of the monopile, the shape of the wings and the soil properties. Another alteration, comprising a monopile combined with a footing base, has also been proposed. Initial model tests performed in sand at 1g were reported by Stone et al. (2007), with apparently promising results, suggesting that the additional rotation restraint provided by the footing can result in a stiffer lateral response and greater ultimate lateral load-carrying capacity. Arshi et al. (2013) performed tests in sand at 1g by adding skirts of different lengths (depths) to these piloted footings. Their results indicated that increasing the skirt length tends to increase the ultimate lateral load-carrying capacity of the foundation system by about 50% compared with the non-skirted hybrid system. More recently, Arshad and O’Kelly (2016b) reported 1g tests in sand that investigated the use of concentric rings of small-diameter piles (SDPs) installed centrally around the model monopile. Their results showed that the rotation of the monopile, investigated under a range of cyclic lateral loading scenarios, was reduced by 40–65% owing to the enhanced confinement and densification of the sand test bed provided by the presence of the SDPs.

This paper presents an experimental investigation performed to explore the possibility of pilehead modification to reduce the accumulated rotation of a monopile under long-term cyclic lateral loading. The novel solution proposed comprises four shorter SDPs, arranged in a cruciform, which attach by way of a grillage to the pilehead at the mudline level. From a review of the literature, this would appear to be the first study of its kind in relation to the proposed set-up for deep foundation structures. On the basis of encouraging results, it can be expected that this novel technique may prove to be a viable solution to enhance the serviceable life of structures supported by monopiles that are subjected to long-term cyclic lateral loading, such as offshore wind-turbine structures (OWTs).

2. Development of the proposed arrangement

2.1 Governing loading for OWT monopile foundation system

Monopile foundations for offshore wind-turbine structures are typically manufactured from steel tubular sections with an outer diameter \(D\) of up to 7.5 m, wall thicknesses of up to 150 mm and embedment depths of between 15 and 30 m (Achmus et al., 2009). Monopile foundations are generally used in shallow water depths (i.e. typically <30 m), generally becoming too flexible for water depths of between ~30 and 40 m, in which case monopiles fitted with guy wires or tripod solutions are considered as economical alternatives. For greater water depths (>40 m), time-consuming installation and the effects of soil degradation ('pothering') that occurs in-service at mudline level around the pile make monopile foundations prohibitive (Irvine et al., 2003). Other foundation options, as discussed by Arshad and O’Kelly (2013, 2016a) and O’Kelly and Arshad (2016), are then considered to be viable. The serviceability limit state is largely determined by the lateral deflection (rotation) response of the monopile under many millions of load cycles, for example, over the service life of a 2 MW OWT structure, 10⁷ lateral load cycles of 1.4 MN magnitude (corresponding to the fatigue loading for design) are expected to occur (Germanischer Lloyd, 2005).

The monopile must mobilise sufficient soil resistance over its embedded length to transfer all types of applied loads to the surrounding soil, with adequate safety factors, and prevent toe ‘kick’ (displacement of the pile base) and excessive deflection/rotation of the pile itself. According to current practice, monopiles are analysed for the axial loads only to determine their bearing capacity and settlement responses, and then for the lateral loads only to determine their lateral load-carrying capacity and flexural behaviour (Karthigeyan et al., 2006; Moayed et al., 2012). Compared with the axial loads, the lateral loads are considered to be governing, as mentioned in several design guidelines (API, 2010; DNV, 2011; Germanischer Lloyd, 2005) and documented by many researchers (Achmus, 2010; Bhattacheriya et al., 2013; Carwell et al., 2015; Haiderali et al., 2013; Kuo et al., 2012; Leblanc et al., 2010; Lombardi et al., 2013; Malhotra, 2010; Nicolai and Ibsen, 2014; Peng et al., 2011; Zhu et al., 2013). In other words, the required diameter, wall thickness and embedment length of the monopile is generally dictated by the applied lateral loads and moments. Hence, the experimental work presented in this paper focuses on the enhancement of the lateral stability of the conventional monopile, with a novel modification to the pilehead proposed, namely four SDPs arranged in a cruciform that attach by way of a grillage to the pilehead.

2.2 Geometric details of proposed arrangement

Figure 1 shows a schematic diagram of the proposed arrangement at reduced scale, which consists of a central 'split-able' ring with four radial steel arms, each fitted with a smaller diameter ring (sleeve ring) at its far end. The two halves of the central ring, manufactured from 30 mm wide x 2 mm thick steel strip, are secured together by way of their collars, using M4 nut-bolts, clamping around the head of the monopole \(D = 53\) mm. Four radial struts welded to the central ring, each having length, width and thickness dimensions of 85, 20 and 2 mm, respectively, were arranged in a cruciform, making the four arms. The far end of each of these arms was
Figure 1. Schematic diagram of cruciform attachment for monopile: (a) plan view; (b) side view (section A–A)

connected by an M4 nut–bolt to a sleeve ring, manufactured from 25 mm wide × 2 mm thick steel strip. The connections between the radial arms and sleeve rings allowed changes to be made to the inclination of the SDPs that were housed in these rings. The sleeve rings were equipped with jacking screws (see Figure 1) that allowed the required adjustments to be made to the solid SDPs (D = 19 mm; i.e. 36% of the monopile diameter) during their installation in the sand beds (described later).

Figure 2 shows the arrangement centred on the monopile, with the four solid SDPs aligned vertically and attached by way of the grillage to the pilehead. Hereafter, the central split-able ring (holding the monopile) and the four radial arms holding the SDPs are collectively termed as the piled-cruciform arrangement.

2.3 Working mechanism of piled-cruciform arrangement

The soil around the monopile is influenced by the cyclic lateral loading (Bhattacharya and Adhikari, 2011; Bhattacharya et al., 2011; Cuéllar et al., 2012; LeBlanc et al., 2010; Rosquoët et al., 2007). For sandy soil, it can be argued that the zone of significant influence remains limited to within 2–3D measured from the monopile axis, as evident from the formation of a cone of depression observed at the sand bed surface level around the monopile during 1g testing (Brown et al., 1988; Cuéllar et al., 2012). For lateral loading, the upper part of the soil deposit around the monopile is more critical than the lower part, owing to the greater level of deflection occurring closer to the pilehead (Nasr, 2014; Zhang et al., 2005).

Conceptually, the piled-cruciform attachment is designed to transfer some of the applied lateral load away from the zone of significant influence for the monopile. Under the action of the applied lateral loading/moment, the monopile and piled-cruciform attachment tend to deflect (rotate with respect to their initial vertical alignment), with resistance provided by the passive pressures (forces) mobilised along the embedded lengths of the monopile and four SDPs (the latter are transmitted by way of the cruciform arms to the pilehead). Through this arrangement, the stress intensity is reduced in the
3. Testing facility, instrumentation and model pile

For the present study, the Trinity College Dublin electromechanical loading system for testing model piles at 1g (Figure 3) was used. This system is capable of applying many thousands of lateral load cycles on scaled models, with full control provided over the loading direction, amplitude, frequency and waveform shape. Further details on its working mechanism and capabilities, including the instrumentation used to measure the lateral loads applied to the pilehead and the resulting axial and lateral deflections and rotation response of the pile (Figure 4) are presented in the paper by Arshad and O’Kelly (2014).

The model pile was manufactured from smooth brass tubing, having an overall length of 540 mm, outer diameter of 53.0 mm and wall thickness of 0.8 mm, which produced a bending stiffness (EI) value of 4.33 kN m². Its lower end was closed using a 3 mm thick brass plate in order to represent a fully plugged tubular pile. Geometrically, the pile set-up, with an embedded length (L) to outer diameter (D) ratio of 6.8 at the start of each loading test performed, is categorised as a short ‘rigid’ pile, which encompasses L/D ratios of up to 10 (DNV, 2011; Peng et al., 2011; Tomlinson, 2001). To verify this, the pile’s rigidity was evaluated based on its value of the dimensionless embedment length, ηL (Broms, 1964). The coefficient η is calculated as

\[ \eta = \left( \frac{k_h}{EI} \right)^{1/3} \]

where \( k_h \) is the initial coefficient of subgrade reaction and \( EI \) is the bending stiffness of the monopile.

According to Terzaghi (1955), the value of \( k_h \) is 19.8 MN/m³ for dense sand (which was the soil investigated in the present study). A pile is considered to be a short rigid pile for \( \eta L < 2 \) and a long elastic pile for \( \eta L > 4 \) (Broms, 1964; Chari and Meyerhof, 1983). The estimated ηL value of 1.94 for the monopile set-up in the present investigation indicates that the model pile satisfied the criterion for short rigid piles.

The model pile was partially embedded in dense sand beds prepared in a 0.95 m dia. by 0.6 m deep steel tank. These dimensions were chosen to ensure that for the static and cyclic lateral loading scenarios investigated in the present study, the failure wedge for the pile would not extend to the tank boundaries. With a ratio of tank diameter to pile diameter of almost 18, side wall boundary effects were not considered to be significant (Davie and Sutherland, 1978; Rao et al., 1996). Similarly, a soil cushion (sand in the present case) having a thickness of 3–4D located below the pile base was considered sufficient to absorb the small vertical stress field (LeBlanc et al., 2010).

4. Sand characterisation and sand bed preparation, including monopile and SDP installation

All of the tests performed used commercially available air-dried Glenview sand, comprising sub-angular to angular grains ranging from 0.1 to 1.0 mm in size, with \( d_{10}, d_{50}, d_{90} \) and \( d_{16} \) values of 0.16, 0.22, 0.27 and 0.31 mm, respectively, giving a coefficient of uniformity value of 1.94 and coefficient of curvature value of 0.98. Furthermore, the sand had minimum and maximum dry density values of 1388 and
1662 kg/m$^3$, respectively, equating to maximum and minimum void ratio values of 0.92 and 0.60, respectively. At maximum density, the dry sand had a peak friction angle of 39°, determined using 60 mm-square shearbox tests.

The sand was air-pluviated into the steel tank, gently raining in six separate layers, each 100 kg in mass. This produced approximately 90 mm thick deposited layers. After the first two layers of sand had been deposited in the tank, the model
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Pile was positioned vertically at the centre of the tank, with temporary support to its head provided by four tensioned horizontal steel wires that were secured radially from the wall of the tank. Four more layers of sand were then deposited, bringing the sand bed to its full depth of 0.54 m (i.e. pile embedment length of 0.36 m). During this process, the surface of the deposited sand layer was levelled, as necessary, using a straight edge before depositing the next sand layer. For all of the sand beds prepared in the present investigation, this preparation technique was found to produce sand beds having a dry density of 1577 ± 6 kg/m³ (density index range of 70–74%). The resulting ‘wished in place’ pile simulated a pre-bored pile; in other words, no displacement would occur in the sand deposit as a result of the pile installation.

On completion of the sand bed with pile installed, the split-able ring attachment was clamped around the pilehead such that its cruciform arms were located just above the finished sand surface level in the steel tank. In the next step, four SDPs were inserted through the sleeve rings and pushed into the sand bed to the required embedment depth (Figure 5). Jacking screws on the sleeve rings (see Figure 1) allowed some fine adjustments before rigidly connecting them to the heads of the SDPs.

### 5. Testing programme

A comprehensive programme of cyclic lateral loading tests (see Table 1) was performed on the model pile in the dense sand beds to evaluate the efficiency of the proposed arrangement. The tests investigated a load amplitude of 60 N, two loading frequencies of 0.25 and 0.4 Hz, and different loading directions (one-way, partial one-way, balanced and unbalanced two-way loading conditions), with typically 12 000 lateral load cycles applied during each test. For one-way loading, the applied load ranged between zero and some maximum load value, whereas for partial one-way loading, the applied load ranged between some value above zero and the maximum load value. With respect to the ultimate static lateral load-carrying capacity ($P_u$) of the pile, the load amplitude of 60 N corresponds to its serviceability limit state (~42% of $P_u$ (DNV, 2011)).

The tests performed are identified as follows: lateral loading direction (1w, one-way; 2w, two-way)/load amplitude (N)/frequency (Hz). For instance, 1w/60/0.25 indicates one-way lateral loading of the monopile (without the piled-cruciform arrangement in situ) for an amplitude of 60 N and frequency of 0.25 Hz. 1w/30–60/0.25 indicates one-way lateral loading, with the load fluctuating from 30 to 60 N from the same side at 0.25 Hz. 2w/30–60/0.4 indicates unbalanced two-way lateral loading, 30 N in one direction and 60 N in the other, applied at a frequency of 0.4 Hz.

Table 2 shows the different formations of the piled-cruciform arrangement investigated (labelled set-ups A–E), namely: (a) ratio of embedment length of the SDPs ($L_{SDP}$) to that of the monopile ($L$); (b) inclination of the SDPs from the vertical direction; (c) orientation of the cruciform grillage with respect to the line of action of the applied loading. For all of the static and cyclic tests performed, the lateral loading was applied to the side of the model pile at an elevation of 90 mm above the sand bed surface level.

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**Table 1. Cyclic lateral loading test programme**

<table>
<thead>
<tr>
<th>Test number</th>
<th>Set-up (refer to Table 2)</th>
<th>Loading scenario (test ID)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference</td>
<td>2w/30–60/0.4</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>2w/30–60/0.4/A</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>2w/30–60/0.4/B</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>2w/30–60/0.4/C</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>2w/30–60/0.4/D</td>
</tr>
<tr>
<td>6</td>
<td>E</td>
<td>2w/30–60/0.4/E</td>
</tr>
<tr>
<td>7</td>
<td>Reference</td>
<td>2w/60–60/0.4</td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>2w/60–60/0.4/A</td>
</tr>
<tr>
<td>9</td>
<td>B</td>
<td>2w/60–60/0.4/B</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
<td>2w/60–60/0.4/C</td>
</tr>
<tr>
<td>11</td>
<td>D</td>
<td>2w/60–60/0.4/D</td>
</tr>
<tr>
<td>12</td>
<td>Reference</td>
<td>1w/60/0.25</td>
</tr>
<tr>
<td>13</td>
<td>A</td>
<td>1w/60/0.25/A</td>
</tr>
<tr>
<td>14</td>
<td>B</td>
<td>1w/60/0.25/B</td>
</tr>
<tr>
<td>15</td>
<td>C</td>
<td>1w/60/0.25/C</td>
</tr>
<tr>
<td>16</td>
<td>Reference</td>
<td>1w/30–60/0.25</td>
</tr>
<tr>
<td>17</td>
<td>A</td>
<td>1w/30–60/0.25/A</td>
</tr>
<tr>
<td>18</td>
<td>B</td>
<td>1w/30–60/0.25/B</td>
</tr>
</tbody>
</table>

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**Figure 5. Piled-cruciform arrangement attached to head of monopile installed in dry sand bed. Note: 1, sand bed surface; 2, protruding head of SDP; 3, sleeve ring; 4, central ‘split-able’ ring; 5, steel tank perimeter; 6, protruding head of central monopile; 7, cruciform arm; 8, miniature load cell attached to pile shaft at a distance of 90 mm above the sand bed surface level.**
<table>
<thead>
<tr>
<th>Set-up</th>
<th>SDP length ($L_{SDP}$) and inclination to vertical direction</th>
<th>Offset of cruciform arms with respect to line of action of applied loading</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td>Cruciform arms are aligned with the line of action of the cyclic lateral loading. Vertical SDPs are half the length of the central monopile ($L$) – that is, $L_{SDP}/L = 0.5$.</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>As per set-up A, apart from the SDPs being one-third of the monopile length – that is, $L_{SDP}/L = 0.33$.</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>Cruciform arms are offset by 45° from the line of action of the cyclic lateral loading. Vertical SDPs are one-third of the monopile length; that is, $L_{SDP}/L = 0.33$.</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>As per set-up B, apart from the SDPs being inclined at 15° to the vertical direction.</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td>As per set-up C, apart from the SDPs being inclined at 15° to the vertical direction.</td>
</tr>
</tbody>
</table>

Table 2. Different set-ups of the piled-cruciform attachment investigated
6. Ultimate static lateral load-carrying capacity of monopile

Static lateral loads were applied in small increments of 10 N to the model pile in order to evaluate its ultimate static lateral load-carrying capacity, with and without the piled-cruciform attachment in situ. The lateral deflection response of the pilehead was monitored using two horizontally mounted displacement transducers (Figure 4), with the transducer readings allowed to stabilise before the application of the next load increment. The rotation response of the rigid pile was calculated using these displacement measurements, as described in the paper by Arshad and O’Kelly (2014).

Different assumptions have been used by researchers regarding the determination of the ultimate static lateral load-carrying capacity, although they are generally based on excessive lateral displacement of the pilehead or rotation of the pile (Hu et al., 2006; Nasr, 2014; Peng et al., 2011). Some researchers determine the value of \( P_u \) as corresponding to a point on the load-deflection (rotation) curve where the pile starts to deflect (rotate) significantly for a relatively small increase in the lateral load (Dickin and Laman, 2003; Prasad and Chart, 1999).

Figure 6 shows the static lateral load-rotation relationships obtained for monopiles having five different piled-cruciform arrangements (set-ups A–E in Table 2) investigated as part of the present study, along with reference data for the monopile alone. Previous studies of rigid, model pile behaviour performed at 1g usually estimated the \( P_u \) value for lateral pile deflections of 0.1–0.2 \( \times D \) (Cuéllar et al., 2012; El Sawaf, 2006; Peng et al., 2011; Uncuoglu and Laman, 2011) occurring at the sand bed surface level. Hence, in the present investigation, the value of \( P_u \) for the reference monopile was estimated as 140 N, which corresponded to a point on its experimental load–rotation curve (Figure 6) where, apparently, the surrounding sand began to yield substantially; that is, its rotation increased by 0.4° over the load increment from 120 to 140 N, whereas it increased by almost 1.0° for the load increment from 140 to 160 N. For this point (140 N), the model pile had rotated by 1.5° from its initial vertical alignment, producing a lateral deflection (measured at the sand bed surface level) of \( \sim 7 \) mm; that is, 0.13 \( \times D \). From Figure 6, it can be interpreted that the inclusion of the different piled-cruciform arrangements all substantially improved the ultimate static lateral load-carrying capacity of the monopile, as summarised in Table 3 for quick comparison.

7. Performance of piled-cruciform arrangement in reducing monopile rotation under cyclic lateral loading

7.1 Effect of SDP embedment length

Twelve tests were performed to investigate the effect of the SDP embedment length on the rotation response of the monopile, considering four different loading scenarios and two \( L_{SDP} \) values of 0.5 and 0.33 (set-ups A and B, respectively, in Table 2). Figures 7(a) and 7(b) show the rotation responses of the monopile for one-way and partial one-way loading, respectively, while Figures 7(c) and 7(d) show its responses for balanced and unbalanced two-way loading, respectively.

![Figure 6. Static lateral load plotted against rotation relationships for the different experimental set-ups shown in Table 2](image-url)
From these figures, it can be interpreted that the piled-cruiform attachment to the monopile considerably reduced its accumulated rotation, when compared with the reference monopile for the same loading condition. For instance, at 6000 load cycles for the unbalanced two-way loading scenario of 2w/30–60/0–40 (Figure 7(d)), the reference monopile had rotated by 2.75°, whereas with the piled-cruiform attachment in situ, its rotation was limited to 0.49° and 0.38° for $L_{SDP}/L$ values of 0.33 and 0.5, respectively; that is, 82% and 86% reductions in the monopile rotation were achieved (as determined using Equation 2). The respective reductions in the monopile rotation were 57% and 68% for balanced two-way loading (i.e. 2w/60–60/0–40 in Figure 7(c)), and 24% and 31% for one-way loading (i.e. 1w/60/0–25 in Figure 7(a)). For partial one-way loading (i.e. 1w/30–60/0–25 in Figure 7(b)), when compared with the reference monopile, the rotation was found to reduce by 73% for both $L_{SDP}/L$ values investigated. The reduction in the monopile rotation can be largely explained by the additional passive resistances mobilised along the

<table>
<thead>
<tr>
<th>Set-up (refer to Table 2)</th>
<th>Lateral resistance: N</th>
<th>Rotation: degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>90</td>
<td>0.5</td>
</tr>
<tr>
<td>A</td>
<td>200</td>
<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>136</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>122</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>106</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>96</td>
<td>0.5</td>
</tr>
<tr>
<td>Reference</td>
<td>150</td>
<td>1.88</td>
</tr>
<tr>
<td>A</td>
<td>150</td>
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<td>0.76</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>0.96</td>
</tr>
<tr>
<td>E</td>
<td>150</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3. Lateral resistance mobilised for 0.5° rotation of monopile, and monopile rotation produced by an applied lateral load of 150 N, for the different set-ups of the piled-cruiform attachment

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Figure 7. Effect of SDP embedment length on accumulated rotation of the monopile: (a) one-way loading; (b) partial one-way loading; (c) balanced two-way loading (d) unbalanced two-way loading
2. Reduction (as %) = \( \left( \frac{a - b}{a} \right) \times 100 \)

where \( a \) is the monopile rotation and \( b \) is the rotation of the monopile with the piled-cruciform attachment in situ.

Figure 8 shows the percentage reduction in the monopile rotation produced when the \( L_{SDP}/L \) ratio was increased from 0.33 to 0.5. From this figure, it can be concluded that, for this 50% increase in the \( L_{SDP}/L \) value, the monopile rotation was reduced by between 9% and 27% over the 12,000 load cycles applied. Hence, for practical purposes, based on these model test results, there is no major benefit achieved in increasing the \( L_{SDP}/L \) ratio from 0.33 to 0.5.

7.2 Effect of loading direction orientation

Six of the tests performed were designed to investigate two different orientations of the piled-cruciform arrangement, with respect to the line of action of the applied loading (set-ups B and C in Table 2), considering three different loading scenarios and an \( L_{SDP}/L \) value of 0.33. Figure 9 shows that relatively greater rotation of the monopile occurred when the cruciform arms were offset by 45° from the line of action of the applied loading (set-up C), as compared with full alignment (set-up B), although the difference was marginal for the one-way and balanced two-way loading scenarios investigated. For instance, at 6,000 load cycles, the monopile had rotated by 0.92° (1w/60°/0.25/C in Figure 9(a)) and 0.73° (2w/60°/60°/0.40/C in Figure 9(b)) for set-up C, compared with 0.88° and 0.69°, respectively, for set-up B. However, the effect was significant for unbalanced two-way loading (2w/30°/60°/0.4 in Figure 9(c)), with monopile rotations of 0.76° and 0.49° measured for set-ups C and B, respectively, at 6,000 load cycles. A possible reason for the greater rotation experienced for set-up C may be the decrease in perpendicular distance (from 125.0 to 88.4 mm) between the SDP centres and the axis of the monopile orthogonal to the loading direction (see Figure 10), which may have the effect of causing some greater overlap between the zones of significant influence for the laterally loaded
monopile and SDPs. For practical reasons, it can be considered that the more favourable orientation occurs for the cruciform arms aligned with the line of action of the applied loading.

7.3 Effect of SDP inclination
The efficiency of the piled-cruiform arrangement was also evaluated for different inclinations (to the vertical direction) of the SDPs at an $L_{SDP}/L$ value of 0.33. For this purpose, the four SDPs were inclined outward, at 15° to the vertical direction, and the monopile tested under balanced and unbalanced two-way loading, with the cruciform arms aligned with the line of action of the applied loading (set-up D in Table 2). Figures 11(a) and 11(b) show the effect of this change in inclination, comparing set-up D with set-up B (see Table 2). From these figures, it can be concluded that, for both of these loading scenarios investigated, the set-up with the inclined SDPs produced greater monopile rotation. For instance, compared with the vertical SDPs (set-up B), the monopile rotation for the SDPs inclined at 15° under balanced two-way loading (2w/60–60/0–4/D in Figure 11(a)) was 5–9% greater than the 1000th and 6000th load cycles. For unbalanced two-way loading (2w/30–60/0–4/D in Figure 11(b)), the corresponding increase was in the range 16–25% (the same percentage range increase also occurring for up to the maximum number of load cycles of 12 000 applied).

Another test was performed for unbalanced two-way loading, with the SDPs inclined at 15°, but with the cruciform arms offset by 45° from the line of action of the applied loading (set-up E in Table 2). Compared with set-up B (i.e. cruciform arms aligned with the lateral loading direction), the monopile rotation for this arrangement (2w/30–60/0–4/E in Figure 11(b)) was 97% greater at the 1000th load cycle, reducing to 74% at the 12 000th load cycle.

A possible reason for the increase in monopile rotation for the inclined SDPs may be their lower resistance against the pulling action of the applied lateral loading, which is certainly greater for vertical SDPs. This hypothesis was investigated by
performing some additional tests, each involving 1500 cycles of unbalanced two-way lateral loading (2w/30–600/0–4), for the same $L_{SDP}/L$ value of 0.33, with the cruciform arms in line with the loading direction, but setting the inclination of the SDPs at 15°, 25° and 40° to the vertical direction (Figure 11(c)).

At the 1500th load cycle, the monopole rotation values for the 25° and 40° settings were found to be 17% and 28% greater compared with the 15° setting. It is the authors' view that it is probable this situation could be reversed if these SDPs were replaced by helical piles of similar dimensions.

8. Effect of piled-cruciform on cyclic stiffness of soil–pile system

The cyclic stiffness of the soil-pile system was calculated and plotted in Figure 12 for the series of tests reported in Tables 1 and 2. The overall trend in the variation of cyclic stiffness with increasing number of load cycles was broadly similar for set-ups with and without the piled-cruciform attached to the monopole. For a given set-up, a marginal overall increase in cyclic stiffness occurred for one-way loading (Figure 12(a)); for example, compared with the reference monopole (1w/600/0–25), the values of cyclic stiffness mobilised with the piled-cruciform attachment in situ (set-ups B and C) were typically 20–30% greater over the 1000–6000 load cycle range. For partial one-way loading (1w/30–600/0–25 in Figure 12(a)), the increase in cyclic stiffness was significantly greater (typically 70–130%) over the same load cycle range for set-ups A and B.

For balanced two-way loading with the piled-cruciform attachment in situ (set-ups A–C in Figure 12(b)), the values of cyclic stiffness increased from ~230 N/mm to 380 N/mm over the 1000–6000 load cycle range (and to 450 N/mm at 10,000 load cycles), whereas the reference data increased from ~170 to 265 N/mm over the same range. For unbalanced two-way loading over the 1000–6000 load cycle range, with the piled-cruciform attachment in situ (considering set-ups A–C in Figure 12(c)), the cyclic stiffness increased from ~350 to 415 N/mm, compared with ~195 to 310 N/mm for the reference data (2w/30–600/0–4). Comparing the responses for set-ups A and B, it was found that the initial values and rates of increase in cyclic stiffness were marginally greater for set-up A, which can be explained by its greater $L_{SDP}/L$ value of 0.5 (compared with 0.33 for set-up B), although overall, the difference was not great. This is consistent with the earlier finding that there was no major benefit (in terms of the reduction in monopole rotation) achieved in increasing the $L_{SDP}/L$ ratio from 0.33 to 0.5 (see Figures 7 and 8).

Achmus et al. (2009), API (2010) and DNV (2011) have suggested that, irrespective of soil type, the stiffness of the soil-pile system degrades under cyclic lateral loading. In contrast, Rosquét et al. (2007), LeBlanc et al. (2010), Bhattacharya et al. (2011) and Cuéllar et al. (2012) have reported that the foundation stiffness actually increases with the number of lateral load cycles, on account of densification of the sandy soil next to the monopole. The present experimental findings also indicate an increase in foundation stiffness with increasing number of lateral load cycles.

The change in stiffness of the soil-pile system with increasing number of load cycles may adversely affect the performance of the structure supported by the monopole. For instance, an
increase in cyclic stiffness of the foundation system would increase its natural frequency of vibration, which could potentially lead to resonance occurring when the forcing frequency and the natural vibration frequency of the system come close to one another. This would cause increased deflection (rotation) of the monopile, which in turn may cause more rapid deterioration of the on-board machinery and, in some cases, may ultimately lead to structural failure (Adhikari and Bhattacharya, 2011). In the case of a strain-hardening site (e.g. loose to medium-dense sand or normally consolidated clay deposit), the natural vibration frequency of the foundation system is expected to increase, whereas for a strain-softening site (e.g. dense sand or overconsolidated clay deposit), its natural frequency of vibration would decrease (Bhattacharya et al., 2011, 2013).

9. Limitations of this study
The present investigation was performed using a model pile, partially embedded in dense sand beds (density index range of 70–74%). Additional testing should be undertaken to evaluate the behaviour of the monopile for other density ranges and different soils types. Further, the field stress conditions can be simulated more adequately within the soil mass (beds) using a centrifuge testing facility, rather than performing the tests at 1g.

It may be a limitation of this study that only 6000 load cycles were applied in some of the tests performed, because the number of load cycles considered for the fatigue limit state of an offshore wind-turbine foundation is significantly greater (Germanischer Lloyd, 2005). It was found that the general trend in the monopile behaviour under cyclic lateral loading had practically stabilised by the 6000th load cycle; that is, although the monopile continues to rotate for greater numbers of load cycles, the experimental data plots presented indicate that this occurs at a decreasing rate. Any quick change in the experimental curve describing the rotation against number of load cycles relationship, as occurred during the first 500 load cycles applied, seems unlikely.

The model pile used in this investigation geometrically represents the field monopile at a scale of approximately 1:100. Among other technical difficulties encountered in performing physical tests with geometries, the direct scaling of the particle (grain) dimensions is particularly problematic. Undesirable forces may be introduced unless a certain minimum ratio is maintained between the effective grain size $d_{50}$ and a characteristic dimension of the model (pile diameter for the present investigation) (Sedran et al., 2001; Verdure et al., 2003). Examples of the derivation of scaling laws for monopile foundation testing at 1g have been reported by Lai (1989), Muir Wood et al. (2002), LeBlanc et al. (2010), Bhattacharya et al. (2011) and Cuellar et al. (2012), although the satisfaction of such scaling conditions for similarity in granular soils, and scaling issues related to the stress field corresponding to homologous points, is not trivial (Bhattacharya et al., 2011; Dong et al., 2001).

10. Conclusions
The improvement in performance produced by the piles-cruiform attachment to the monopile head was investigated for many thousands of lateral load cycles. Based on the results of the different series of tests presented, the following conclusions can be drawn.

(a) The accumulated rotation of the monopile was dependent on the cyclic load characteristics, the embedment depth and inclination of the SDPs and the loading direction orientation (i.e. orientation of the cruciform arms relative to the line of action of the applied loading).

(b) For four vertical SDPs having $L_{SDP}/L$ values of 0.33 and 0.5, the greater reduction in monopile rotation at 6000 load cycles was recorded for unbalanced two-way loading (82% and 86%, respectively), followed by partial one-way loading (73% for both), balanced two-way loading (57% and 68%, respectively) and finally one-way loading (24% and 31%, respectively). The performance of the piled-cruiform modification reduced when the cruciform arms were offset by 45° from the line of action of the applied loading.

(c) The monopile rotation reduced for greater embedment of the SDPs, although for the $L_{SDP}/L$ values of 0.33 and 0.5 investigated, comparable overall reductions in the monopile rotation were achieved for the experimental conditions investigated. Hence, the shorter SDPs (i.e. one-third of the monopile length) may be adequate for practical purposes.

(d) Vertical SDPs were more efficient in reducing the accumulated rotation of the monopile compared with SDPs inclined at 15°, 25° and 45° (the last of these was the least efficient among those investigated) to the vertical direction.

For the prototype, the cruciform arms have to be strong and stiff enough to transmit the forces and the monopile will possibly require some strengthening near the head level (possibly achieved through increased wall thickness of the monopile) to avoid buckling.

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REFERENCES


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