Centrifuge modelling of laterally loaded single battered piles in sands

Limin Zhang, Michael C. McVay, and Peter W. Lai

Abstract: Centrifuge lateral load tests were performed on single battered piles at five pile inclinations founded in both medium-dense (relative density $Dr = 55\%$) and loose ($Dr = 36\%$) sands. The effects of pile batter and soil density on lateral resistance were studied. Pile batter had significant effects in dense sands but minor effects in loose sands. Based on the test results, nonlinear $p$–$y$ curves, where $p$ is the soil resistance in unit length and $y$ is the lateral deflection of the pile, were developed for single piles at any angle (positive or negative) and sand density. The developed $p$–$y$ curves were subsequently used with a Winkler model (COM624, LPILE, FLPIER, etc.) to predict all the test results with reasonable accuracy.

Key words: laterally loaded pile, battered pile, centrifuge model test, $p$–$y$ curve, numerical analysis.


Mots clés : pieu chargé latéralement, pieu incliné, essai sur modèle au centrifuge, courbe $p$–$y$, analyse numérique

Introduction

Generally, a pile will carry much larger axial loads than lateral loads. Through battering, a designer expects to transfer a portion of the lateral load to axial load, thereby increasing the lateral capacity of a pile group. Battered pile groups are widely used in deep water or scour regions to resist large lateral loads (ship impact, earthquake, etc.).

Unfortunately, the lateral resistance of single battered piles is not well understood because of the scarcity and inconsistency of test data. For instance, Matsuo (cited in Tschebotarioff 1953) conducted pullover model tests in dry sand and found that a plumb pile developed the largest lateral resistance, followed by piles loaded against the batter direction (positive batter in Fig. 2), and finally by piles loaded in the batter direction (negative batter in Fig. 2). Kubo (1965) conducted similar tests in dry dense river sand (density of 17.45 kN/m$^3$) and found that the plumb pile resistance was smaller than that of the piles battered against the loading direction (positive batter) but larger than that of the piles battered in the loading direction (negative batter). Meyerhof and Ranjan (1972, 1973) and Meyerhof and Yalcin (1993, 1994) also conducted extensive model tests to investigate the behaviour of flexible battered piles under vertical or eccentric inclined loads. These tests indicated that the bearing capacity depended on the soil structure, load eccentricity, load inclination, and pile batter. Rao and Veeresh (1994) performed model tests on 12 mm diameter aluminium piles of three lengths in a soft marine clay. Their test results revealed that the lateral capacity of the pile increased when the pile batter angle increased from $-30\%$ to $30\%$ (see Fig. 2). Reported field tests on battered piles are scarce. In the field tests conducted by Awoshika (1971), both plumb piles and piles battered against the load direction (positive batter) presented larger soil resistance than those battered in the load direction (negative batter). Alizadeh and Davisson (1970), Kim and Brungabler (1976), and Kim et al. (1979) conducted field tests comparing the response of a plumb pile with that of a battered pile at a single inclination. Their results were inconclusive using the generalized nondimensional approach developed by Matlock and Reese (1960), which assumes a similar response for battered and plumb piles.

Several methods have been proposed for analysing single battered piles. Awad and Petrasovits (1968) and Prakash and Sharma (1990) suggested that a plumb pile subjected to an inclined load at an angle $\alpha$ was equivalent in behaviour to a battered pile inclined at an angle $\alpha$ subjected to a vertical load. However, such equivalency was not extended to lateral loading. Moreover, the resistance predicted using such a
method would not be sensitive to loading directions relative to the pile batter (i.e., plus or minus batter angle). Meyerhof and Ranjan (1972) and Meyerhof and Yalcin (1994) evaluated the capacity of flexible piles by analysing them as equivalent rigid piles with an ultimate effective embedment depth. The ultimate central load $Q_u$ was then estimated by a semiempirical equation that related $Q_u$ to its axial and normal components, $Q_{ua}$ and $Q_{un}$ respectively (Meyerhof and Ranjan 1972). This method is versatile in taking into account the effects of foundation structure, pile batter, and load inclination. However, it is subjected to the rigid equivalent pile assumption. More recently, Rao and Veeresh (1994) suggested that the relationship between pile head deflection, $y$, and $y^2/[P(\alpha + 50)^{0.5}]$ is an unique one, where $P$ is the lateral load at the pile head in Newtons, and $\alpha$ is the pile batter angle. At a specified pile head deflection, $y$, this relationship assumes that the lateral load, $P$, varies only with $(\alpha + 50)^{0.5}$, regardless of pile and soil properties. This may not be generally valid, since the effects of pile batter depend closely on the soil and pile properties.

With the advances in both computer hardware and software strategies, the $p-y$ method presented by McClelland and Focht (1958), where $p$ is the soil resistance in unit length and $y$ is the lateral deflection of the pile, has enjoyed great success in modelling lateral soil–pile response. A variety of such curves has been developed for sand (Reese et al. 1974; O'Neill and Murchison 1983) and clays (Matlock 1970; Reese and Welch 1975; Gazioglu and O'Neill 1984). These nonlinear curves have been adopted in several numerical codes, such as COM624P (Wang and Reese 1993), LPILE (Reese 1985), and the Coupled Bridge Superstructure–Foundation Interaction Finite Element Program FLPIER (McVay et al. 1996a). Such codes generally have a multitude of $p-y$ curves for specific soils and loading conditions (static, cyclic) which are generally employed for both plumb and battered piles. Recently, Bowles (1996) proposed a method for adjusting subgrade modulus used in the $p-y$ curve for battered pile behaviour based on both the passive earth pressure and side shear. However, the adjusted soil modulus for all batter angles was always significantly larger than its plumb counterpart, which may not agree with experimental results.

This research was intended to provide experimental data concerning the behaviour of single battered piles and develop nonlinear $p-y$ curves for battered piles in sands. Centrifuge tests were carried out because of their cost effectiveness, their ability to simulate the prototype behaviour, and the speed in which they could be accomplished.

**Centrifuge apparatus and model piles**

An in-flight pile installation system developed earlier for battered pile group installations (McVay et al. 1996b) was employed for this study. Fig. 1 shows a schematic of the testing apparatus. The equipment allowed the battered piles to be jacked into the soil row by row and laterally loaded without stopping the centrifuge.

During the installation process, the piles were oriented at the specified inclination with the pneumatic cylinders (Fig. 1, A) and a template. The inclination of the piles, the same as the piston rods, was controlled by the angles of the piston base block (Fig. 1, N). The support column (Fig. 1, B) supported two pairs of pistons, one with a 1:0.125 (vertical to horizontal) inclination and another with a 1:0.25 inclination in the opposite direction. For the plumb pile tests, the...
An inclined piston base block was replaced with a flat or horizontal base block. To guide the pile during installation, a small rod (Fig. 1, G) was attached to the end of the piston rod and the pile cap. When the piles were fully installed, the centre of the pile cap (Fig. 1, F) was at the same elevation as the lateral loading rod (H). Subsequently, the pile installation pistons were retracted and the free-standing pile was ready for lateral loading by an air cylinder (Fig. 1, E). Reversing the support column (Fig. 1, B) that rested on the base plate (I) would change the pile batter direction relative to the lateral loading rod. The lateral load was measured by a load cell (Fig. 1, L) fixed on the end of the loading rod (H). The lateral movement of the pile cap was measured with a linearly variable displacement transducer (LVDT), but the axial displacement of the model piles was not measured. The data-acquisition system consisted of a personal computer with a 16-bit HRES card and three EXP-20 multiplexers with a total of 48 voltage channels.

The air control system consisted of an air compressor, a double-port pneumatic rotary union (on centrifuge), two solenoid air valve manifolds (four valves each on the centrifuge), and a switchboard in the control room. The air pressure for pile installation and lateral loading was regulated, whereas that for retracting the piles was unregulated, i.e., 760 kPa.

Shown in Fig. 2 is the layout of the single battered pile tests. Five pile inclinations were tested for each soil density, i.e., 1:0.25, 1:0.125, plumb, 1:–0.125, and 1:–0.25. Each test case was repeated twice to assess accuracy. The square aluminium model piles were 304 mm (12 in.) long and 9.5 mm (0.375 in.) wide. The model tests were conducted at 45 times the earth’s gravitational field. In prototype scale, the width, total length, and embedded length of each square pile were 0.43, 13.7, and 10.9 m, respectively, as in the pile group tests (Zhang et al. 1999). The lateral load was applied at the centre of one end of the pile cap, which was approximately 0.57 m below the pile head. The free length, i.e., the distance between the point of lateral load application and the ground surface, varied from 2.14 m for the battered piles in the medium-dense sand to 2.54 m for the plumb pile in the loose sand. The Young’s modulus of the model aluminium was 73.1 MPa, and the flexural stiffness of a prototype single pile was $EI = 206$ MN·m$^2$. Assuming the coefficients of subgrade reaction $n_h = 1.36$ and 2.71 MN/m$^3$ for the loose and dense sands, respectively, the characteristic length of the pile–soil system (Matlock and Reese 1960) was computed as 4.0–4.6 times of the embedded pile length. The piles, therefore, could be considered as “long piles” that would not develop significant lateral displacement and rotation at their tips.

**Test soil**

The soil used in the study was a sand, referred to hereafter as mixed sand, which was a blend of multiple gradations of Edgar-Allen sand. The gradation of the mixed sand is shown in Fig. 3, with the average particle diameter being 0.23 mm. Since this sand had been used for prior testing (i.e., plumb and battered pile group studies), its present gradation was found to be finer than its earlier reported values (McVay et al. 1997, 1998) (see Fig. 3).

The test samples were prepared by dry pluviation through three rectangular sieves (U.S. standard sieve No. 14) which were stacked on top of the rectangular sample container. Two sample densities were prepared for the tests: (1) loose sand with a relative density $Dr = 36\%$, and (2) medium-dense sand with a relative density $Dr = 55\%$. The dry unit weights corresponding to these relative densities were 14.05
and 14.50 kN/m$^3$, respectively. Originally, the internal friction angles of the sands were 34.5° and 37.1° (McVay et al. 1997, 1998). However, after repeated use, new triaxial tests indicated that the friction angles had reduced to 30.8° and 33.3°, respectively.

**Test results**

The test results were reported in prototype scales. For instance, the prototype displacement and force were $N$ and $N^2$ times their measured model values, respectively, where $N = 45$ was the model scale.

Presented in Fig. 4 is the response of the single piles in the medium-dense sand (Dr = 55%). The load versus deflection plots show that the pile batter has a significant effect on the lateral resistance. The piles battered against the loading direction (positive batter, Fig. 2) show larger resistance than the plumb pile, whereas those battered in the loading direction (negative batter) show less resistance than the plumb pile.

Presented in Fig. 5 is the response of the single piles in the loose sand (Dr = 36%). The figure suggests that the lateral load–deflection curves for all five tests fall within a narrow band. Although the increase in resistance with positive pile batter is noticeable, the increase is not significant and
for all practical purposes the effects of pile batter (1:–0.25 to 1:0.25 inclinations) in loose sand are minor.

Summarized in Figs. 6a and 6b are the relationships between batter angle and the ratios of battered pile resistance to plumb pile resistance and battered pile soil resistance to plumb pile soil resistance, together with the data measured in the centrifuge tests. The general trends in Fig. 6 indicate that the lateral resistance (pile and soil) depends on both pile batter and soil density. For very loose sand (Dr = 20%), the dependence of lateral resistance on pile batter is minimal (Meyerhof and Yalcin 1994). This dependency becomes more and more significant with increasing sand density, as identified from the centrifuge tests in loose (Dr = 36%) and medium-dense (Dr = 55%) sands and the conventional tests reported by Kubo (1965) in dense sand. The increases in resistance are 4, 14, 24, and up to 50% in the very loose, loose, medium-dense, and dense sands, respectively, at positive pile batter (1:0.25) versus plumb piles. The percentages of resistance decrease are 4, 5, 15, and up to 35%, respectively, for negative pile batter (1:–0.25) versus plumb piles.

There were inconsistencies (soil variability, fabrication, etc.) with all tests, which resulted in conflicting data. For instance, the field results from Alizadeh and Davison (1970) and the model tests by Meyerhof and Yalcin (1994) in clay showed that the plumb piles developed the smallest resistance. However, the model test results by Matsuo (cited in Tschebotarioff 1953) showed that the plumb pile was stronger than battered piles with either positive or negative batter. A possible explanation for the latter is that the lateral resistance of a pile is sensitive to its free length (i.e., distance between the point of lateral load application and the ground surface). In the centrifuge tests in loose sand (see Fig. 5), the plumb pile resistance was less than the battered pile (in direction of loading) resistance, since the free length of the plumb pile (2.54 m) was larger than that of the battered piles (2.29 m). However, after correcting the free length of the plumb pile to the battered pile value (2.29 m) (to be discussed), the plumb pile resistance fell between the piles battered in and against the loading direction, as shown in Fig. 6a.

The influence of sand density on the lateral resistance can be explained in part by the stress–strain behaviour of sands. For laterally loaded piles in dense sand, the soil in front of the pile–shaft exhibits dilatancy and a full passive failure wedge is likely to occur (Reese et al. 1974). Consequently, the pile resistance depends on the shape of the passive soil wedge, which is strongly influenced by the pile batter. If the pile is founded in loose sand, the soil in front of the pile will undergo volumetric compression, which limits the development of the passive wedge (i.e., size and extent around the pile). As a result, changing the pile batter will alter the pile’s resistance to a much lesser degree.

Nonlinear \( p-y \) curves for battered piles

Nonlinear \( p-y \) curves for battered piles have not been discussed much in the literature. Awoshika (1971) suggested that a \( p-y \) curve for battered piles be obtained by modifying the ultimate soil resistance of a plumb pile \( p-y \) curve with a factor that could be determined from the measured relationship between batter angle and soil resistance ratio similar to that in Fig. 6b. However, such a relation would require significant experimental testing (e.g., varying soil type, soil density, pile type, and pile shape).

Figs. 4 and 5 show that the lateral resistances of the battered piles are different from those of the plumb piles at both small and large deflections. In developing the composite plumb pile \( p-y \) curve for sand, Reese et al. (1974) focused on both initial slope (see OA in Fig. 7) and the final or ultimate resistance (see CD in Fig. 7) which govern the pile response at small and large deflections, respectively. Consequently, two of the most important soil parameters are the
Fig. 6. Summary of the test results: influence of pile batter on (a) lateral pile resistance, and (b) soil resistance. \( L \) = embedded pile length; \( D \) = pile diameter.

The initial subgrade modulus \( k_s \) and the ultimate soil resistance \( p_u \) (controlled by unit weight and angle of internal friction) along lines similar to those of the Reese et al. development, it is proposed that the plumb pile \( p-y \) curves for battered piles be modified through these two parameters. That is, the shape of the battered pile \( p-y \) curve (Fig. 7) remains the same as that of the Reese et al. curve, but the initial subgrade modulus \( k_{sb} \) and ultimate soil resistance \( p_{ub} \) vary with pile batter angle. Also, it is proposed that the change in both the subgrade modulus \( k_{sb} \) and the soil’s ultimate resistance \( p_{ub} \) be proportional to the ratio of passive earth pressure coefficients determined from vertical and inclined walls. Therefore, the ultimate soil resistance of a battered pile, \( p_{ub} \), may be expressed as a simple function of the Reese et al. plumb pile ultimate soil resistance, \( p_u \), as

\[ p_{ub} = \psi p_u \]

where \( \psi \) is given as

\[ \psi = \lambda \frac{K_{pb}}{K_p} \]

and \( K_{pb} \) and \( K_p \) are the passive earth pressure coefficients for an inclined wall and a vertical wall, respectively; and \( \lambda \) is a coefficient that accounts for the size of the sand’s passive soil wedge through its relative density. As shown in Fig. 8 (diagram of an inclined wall) the passive pressure coefficient can be calculated according to Coulomb’s theory (Liu and Evett 1987):

\[ K_p = \frac{\sin^2(\theta - \varphi)}{\sin^2\theta \sin(\theta + \delta)} \left[ \frac{1}{1 - \frac{\sin(\varphi + \delta) \sin(\varphi + \beta)}{\sin(\varphi + \delta) \sin(\varphi + \beta)}} \right]^2 \]

where \( \theta \) is the wall inclination (and pile batter proposed herein \( \alpha = \theta - \pi/2 \)); \( \phi \) and \( \delta \) are the internal friction angle of...
the soil and the friction angle on the soil–pile interface, respectively; and $\beta$ is the ground slope angle, which for the wall or for piles herein is zero.

Similarly, the initial subgrade modulus for battered piles, $k_{sb}$, is obtained by modifying the plumb pile subgrade modulus, $k_s$, with the same factor $\psi$:

$$k_{sb} = \psi k_s$$

For sands, the subgrade modulus can be assumed to increase linearly with depth $z$:

$$k_{sb} = n_{hb} z$$

where $n_{hb}$ and $n_{h}$ are the coefficients of subgrade reaction of the battered and plumb piles, respectively.

As will be discussed later in the paper, the pile wall friction angle, $\delta$, has a considerable influence on the lateral resistance of battered piles, in addition to the skin friction of axially loaded piles. Sherif et al. (1982) indicated that the magnitude of $\delta$ depends not only on the soil properties but also on the amount and direction of wall movement. Jardine and Chow (1996) found that the $\delta$ value is independent of relative density and tends to decline with particle size. The Italian AGI design procedures (Mandolini 1997) suggest the use of $\delta = 20^\circ$ for steel driven piles in both loose and dense sands and $\delta = 0.75 \phi$ for precast concrete driven piles. Values of $\delta = (0.5 – 0.8) \phi$ are commonly recommended for the design of concrete piles (Das 1999; Bowles 1996). The Canadian Geotechnical Society (1985) also proposed a value of tan $\delta = (0.7 – 1.0) \tan \phi$, depending on the pile material and pile installation method. Judgement must be used in choosing the value of $\delta$.

The strain required to mobilize the Coulomb passive pressure is very large. For example, experimental evidence indicates that the mobilization of full passive resistance requires a wall movement of the order of 2–4% of embedded depth for dense sands and 10–15% for loose sands (Craig 1997; Fang et al. 1994). In this study, the maximum lateral deflection at the pile head was about 150 mm. The latter may be large enough to develop the passive soil wedge above the centre of rotation in dense sands, but significantly smaller than that required for loose sands in front of a pile (wall). The coefficient $\lambda$ is therefore introduced to account for the deficiency of Coulomb's theory in the case of medium-loose to loose sands. This coefficient can be expressed as

$$\lambda = 1 - f(\text{Dr}) \sin \alpha$$

where $\alpha$ is the pile batter angle, Dr is the relative density of sand, and $f(\text{Dr})$ is a function of relative density. The $f(\text{Dr})$ values for the centrifuge tests in the loose sand (Dr = 36%) and the Meyerhof and Yalcin (1994) tests in a very loose sand (Dr = 20%) were back-calculated through numerical modelling of the pile response using the described procedure. An empirical linear relation was constructed for $f(\text{Dr})$ based on these data, as shown in Fig. 9. After correction with $\lambda$ (eq. [7]), the predicted effects of pile batter using eq. [2] are found to be minor for very loose sands.

The $p$–$y$ parameters for both single piles and groups of piles in the current test sand have been studied by Zhang et al. (1998, 1999), who found that the coefficient of subgrade reaction $n_{hb}$ was 2.714 MN/m$^3$ for the medium-dense sand and 1.357 MN/m$^3$ for the loose sand. The internal friction angles determined by triaxial tests were $\phi = 30.8^\circ$ for the loose sand and $\phi = 33.3^\circ$ for the medium-dense sand. Using these data, the $K_p$ and $\psi$ factors were determined along with the $n_{hb}$ and $p_{ub}$ values for the five pile inclinations, i.e., $\alpha = 14.04^\circ$, 7.13°, 0.00°, $-7.13^\circ$, and $-14.04^\circ$, and are summarized in Tables 1–4. It should be noted that the soil–wall (pile) interface friction angle $\delta$ has a significant effect on the $p$–$y$ curves. Specifically, the larger the $\delta$ value, the larger the $n_{hb}$ and $p_{ub}$ values for positive battered piles and the smaller

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the values for negative battered piles versus plumb pile values. For the aluminum model piles with smooth pile walls in the loose and medium dense sands, a lower bound value of $d = 17^\circ$ was appropriate. The value of $d = 0^\circ$ was also selected for comparison purposes.

Using the proposed $p-\gamma$ modifications (Tables 1–4) and the FLPIER code (McVay et al. 1996a), the single pile response was predicted for all batters and soil densities (i.e., loose and medium dense). Fig. 10a shows the predicted and measured results for the battered piles in the medium-dense sand with $d = 17^\circ$. Apparent in the figure is the reasonable match between the predicted and measured results for all batter angles. Fig. 10b shows the predicted and measured battered pile results in the medium-dense sand using $d = 0^\circ$. Note that the predicted values fall within a narrower range than the measured values, and the influence of pile batter is diminished (see earlier discussion of $d$). Fig. 11 shows the comparisons of the measured and predicted responses of the battered piles in the loose sand using both $d = 0^\circ$ and $17^\circ$. As can be seen, the predictions with $d = 17.0^\circ$ (Fig. 11a) agree very well with the measured curves. However, the predictions with $d = 0^\circ$ for different pile batters show very small differences (Fig. 11b). Based on the latter, it is concluded that the rough pile–soil interface friction angle ($d = 17^\circ$ in this study) should be used for estimating $\psi$ and $K_p$.

In a typical case of pile groups, the top of the battered piles is restrained. Preliminary studies (McVay et al. 1997) reveal that the $p-\gamma$ curves and soil parameters derived from free-head single pile tests can simulate the 3×3 and 4×4 fixed-head battered pile groups in dry sands reasonably well. Limitations

The proposed method is subject to several limitations. First, the model tests were performed in dry sand. In the case of submerged sands, the coefficient of subgrade reaction and ultimate soil resistance would be different from those for dry sand. Second, both the centrifuge tests and numerical analysis indicated the large influence of pile free length. However, the free length in this study varied in a small span, i.e., 2.14–2.54 m. Future experiments need to be performed using pile free length as a test variable.

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Table 1. Predicted factor of pile batter, $\psi$, and the coefficient of subgrade reaction, $n_{hb}$, for battered piles in the medium-dense sand ($\phi = 33.3^\circ$, $\delta = 17.0^\circ$, Dr = 55%).

<table>
<thead>
<tr>
<th>Batter angle (°)</th>
<th>$\psi$</th>
<th>$n_{hb}$ (MN/m$^3$)</th>
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<tbody>
<tr>
<td>14.04</td>
<td>13.40</td>
<td>5.60</td>
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<tr>
<td>7.13</td>
<td>8.91</td>
<td>3.73</td>
</tr>
<tr>
<td>0.00</td>
<td>6.49</td>
<td>2.13</td>
</tr>
<tr>
<td>$-7.13$</td>
<td>5.09</td>
<td>2.13</td>
</tr>
<tr>
<td>$-14.04$</td>
<td>4.23</td>
<td>1.77</td>
</tr>
</tbody>
</table>

Table 2. Predicted factor of pile batter, $\psi$, and the coefficient of subgrade reaction, $n_{hb}$, for battered piles in the medium-dense sand ($\phi = 33.3^\circ$, $\delta = 0^\circ$, Dr = 55%).

<table>
<thead>
<tr>
<th>Batter angle (°)</th>
<th>$\psi$</th>
<th>$n_{hb}$ (MN/m$^3$)</th>
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<tbody>
<tr>
<td>14.04</td>
<td>5.18</td>
<td>4.09</td>
</tr>
<tr>
<td>7.13</td>
<td>4.13</td>
<td>3.26</td>
</tr>
<tr>
<td>0.00</td>
<td>3.43</td>
<td>2.71</td>
</tr>
<tr>
<td>$-7.13$</td>
<td>2.97</td>
<td>2.35</td>
</tr>
<tr>
<td>$-14.04$</td>
<td>2.67</td>
<td>2.11</td>
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</table>

Table 3. Predicted factor of pile batter, $\psi$, and the coefficient of subgrade reaction, $n_{hb}$, for battered piles in the loose sand ($\phi = 30.8^\circ$, $\delta = 17.0^\circ$, Dr = 36%).

<table>
<thead>
<tr>
<th>Batter angle (°)</th>
<th>$\psi$</th>
<th>$n_{hb}$ (MN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.04</td>
<td>10.79</td>
<td>1.98</td>
</tr>
<tr>
<td>7.13</td>
<td>7.50</td>
<td>1.59</td>
</tr>
<tr>
<td>0.00</td>
<td>5.63</td>
<td>1.36</td>
</tr>
<tr>
<td>$-7.13$</td>
<td>4.51</td>
<td>1.23</td>
</tr>
<tr>
<td>$-14.04$</td>
<td>3.82</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 4. Predicted factor of pile batter, $\psi$, and the coefficient of subgrade reaction, $n_{hb}$, for battered piles in the loose sand ($\phi = 30.8^\circ$, $\delta = 0^\circ$, Dr = 36%).

<table>
<thead>
<tr>
<th>Batter angle (°)</th>
<th>$\psi$</th>
<th>$n_{hb}$ (MN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.04</td>
<td>4.50</td>
<td>1.50</td>
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<tr>
<td>7.13</td>
<td>3.66</td>
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<td>0.00</td>
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<td>$-7.13$</td>
<td>2.72</td>
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<tr>
<td>$-14.04$</td>
<td>2.47</td>
<td>1.34</td>
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Fig. 10. Comparisons of measured and FLPIER-predicted responses of the battered piles in medium-dense sand: (a) $\delta = 17^\circ$, and (b) $\delta = 0^\circ$.

Conclusions

Lateral load tests on the single battered piles were conducted to large deflections in a centrifuge at 45g. These tests simulated prototype single square piles 0.43 m wide and 13.7 m long founded in loose and medium-dense sand. Five pile inclinations were modelled: 1:0.125 and 1:0.25 at negative pile batter, plumb, and 1:0.125 and 1:0.25 at positive pile batter.

The lateral pile resistance was influenced by pile batter and soil density. Based on the centrifuge test results and data reported in the literature, the resistance increases over plumb piles were 4, 14, 24, and up to 50% in very loose, loose, medium-dense, and dense sands, respectively, at positive 1:0.25 batter. In contrast, the resistance decreases over plumb piles were 4, 5, 15, and up to 35%, respectively, at negative 1:0.25 batter. The effects of pile batter were significant in medium-dense and dense sands, but minor in loose and very loose sands.

A modified $p-y$ curve for modelling lateral soil–pile interaction was proposed for single battered piles in sands. In this new method, the coefficient of subgrade reaction $n_{ho}$ and ultimate soil resistance $p_{u1}$ for battered piles can be calculated by multiplying the respective plumb pile values by a factor $y_{il}$, which is a simple function of the pile batter and soil properties. The proposed $p-y$ curve was employed to simulate the test piles; the predicted results compared reasonably well with the measured pile response.

It should be noted that the model tests were performed in dry sand, therefore caution should be taken in using the test results for submerged sands, and the modified $p-y$ curve was verified with a small range of pile free lengths.
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References


Fig. 11. Comparisons of measured and FLPIER-predicted responses of the battered piles in loose sand: (a) $\delta = 17^\circ$, and (b) $\delta = 0^\circ$. 

![Graph](I:\cgj\CGJ36\CGJ12\T99-072.vp)