Understanding inner friction mechanism of open-ended piles – an experimental study

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ABSTRACT

An open-ended pile can produce a bearing capacity similar to a closed-ended pile depending on inner frictional resistance, $Q_{an}$, which depends on the degree of soil plugging. The degree of soil plugging may depend on many factors including pile outer diameter ($D$), tip thickness ($t$), sleeve height ($l$) and relative density ($D_t$). In this research, we studied the effects of $t$, $D$ and $l$ on bearing capacity using laboratory scale model piles. The tests were conducted on a medium dense sandy ground using model piles with different values of $D$, $t$ and $l$. The results showed that bearing capacity increases with $t$, which can be attributed to increase in annular area. They also showed that soil plug height, $h$ is dependent of $l$ for larger diameter piles. The results of incremental filling ratio (IFR) showed that penetration of straight piles (i.e., no sleeve) is closer to unplugged state than the piles with a sleeve. While $Q_{an}$ is independent of $l$ for smaller diameter piles ($D=30$ mm), it is dependent of $l$ for larger diameter piles ($D=50$ mm). The results of $Q_{an}$ suggested that as large as 50% of $Q_t$ ($Q_t$ is total resistance) is contributed by $Q_{an}$ even with a small $l$ (e.g., 10 mm) for smaller diameter piles, while $Q_{an}$ in larger diameter piles increases with $l$ and requires $2D$ of $l$ to produce a large as 50% of $Q_t$ by $Q_{an}$.

Keywords: bearing capacity, inner frictional resistance, model test, open-ended pile, sand, soil plug length

1 INTRODUCTION

In recent times, open-ended steel piles have gained popularity over closed-ended piles, particularly in offshore deep foundations. A long open-ended pile, such as the piles used in offshore foundations, can produce a bearing capacity similar to a closed-ended pile due to the large inner frictional resistance mobilised between the inner pile shaft and inner soil (Lehane and Randolph, 2002). The ultimate bearing capacity of an open-ended pile, $Q_{u}$ consists of three components as given in Eq. 1a (see Fig. 1 also).

$$Q_{u} = Q_{an} + Q_{out} + Q_{plug} \quad (1a)$$

$$Q_{plug} = \min (Q_{an}, Q_{b}) \quad (1b)$$

Where $Q_{an}$ is annulus resistance, $Q_{plug}$ is soil plug resistance (see Eq. 1b), $Q_{out}$ and $Q_{in}$ are outer and inner frictional resistance respectively, and $Q_{b}$ is base resistance.

When an open-ended pile is driven into a soil, underneath soil penetrates into the pile and generate a soil plug. Depending on the degree of soil plugging, an open-ended pile can produce a bearing capacity similar to a closed-ended pile. However, in practice, most piles are driven under partial plugged mode (Tomlinson, 2004; Kikuchi, 2011). Fig. 2 shows the modes of the penetration for an open-ended pile.

Many aspects of pile installation and ground conditions can affect the formation of soil plug length (Paik and Salgado, 2004). The uncertainty of the

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knowledge of soil plug length has led different design methods adopting different design parameters for open-ended piles. In Japan, most of the pile foundations are designed based on JRA specifications for highway bridges (JRA, 2002), which specifies the ratio of embedment length to pile outer diameter as the main factor governing inner frictional resistance regardless of the ground conditions. However, the ICP method considers inner diameter and relative density as the main factors governing soil plugging and base capacity (Jardine and Chow, 1996). The main problem with many design methods including the ICP method arises due to the classification of the piles either to fully plugged or unplugged mode whereas most of the piles in practice are driven under partially plugged mode. As partially plugged piles can be classified to unplugged mode, the design methods may underestimate the bearing capacity of open-ended piles. Reviews of widely used current design methods can be found in Lehane et al. (2005) and Schneider at al. (2008). As reported in many design methods, it can be seen that evaluation of inner frictional resistance has not been universally established due to uncertainty of the formation of soil plug length.

In the past, while the effects of ground conditions on soil plug formation have been sufficiently investigated (Paik and Salgado, 2002; Paik et al., 2003), the effects of pile conditions such as wall thicknesses at the pile tip, pile diameters and heights of sleeve (i.e., internal attachment at the pile tip) on the formation of soil plug have scarcely been studied. In this research, open-ended piles with different outer diameters and sleeve heights were tested to study the effects of these parameters on the bearing capacity, particularly inner frictional resistance.

2 METHODOLOGY

2.1 Ground preparation

The loading apparatus is shown in Fig. 3. The model ground was prepared in a soil tank with the dimension of 300 mm inner diameter and 250 mm height. The bearing house fitted on the top cover was designed to maintain the verticality of the driven piles. Silica sand #5 was used to prepare the model ground. The physical properties of silica sand #5 are given in Table 1 and particle size distribution is shown in Fig. 4. The model ground was prepared with 60% of relative density, \( D_r \). Sands were poured from a tube of 30 mm diameter from a constant height to produce the required relative density (i.e., air pluviation method).

![Fig. 3. A photograph of the loading apparatus](image)

Table 1. Physical properties of silica sand #5

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of uniformity, ( C_u )</td>
<td>1.446</td>
</tr>
<tr>
<td>Coefficient of curvature, ( C_c )</td>
<td>0.926</td>
</tr>
<tr>
<td>Particle density, ( \rho_s ) (kg/m(^3))</td>
<td>2647</td>
</tr>
<tr>
<td>Maximum dry density, ( \rho_{d,max} ) (kg/m(^3))</td>
<td>1567</td>
</tr>
<tr>
<td>Minimum dry density, ( \rho_{d,min} ) (kg/m(^3))</td>
<td>1278</td>
</tr>
<tr>
<td>Maximum void ratio, ( \varepsilon_{max} )</td>
<td>1.072</td>
</tr>
<tr>
<td>Minimum void ratio, ( \varepsilon_{min} )</td>
<td>0.689</td>
</tr>
</tbody>
</table>

![Fig. 2. The modes of penetration of an open-ended pile: (a) fully coring, (b) partially plugged and (c) fully plugged mode](image)
### 2.2 Testing method

Static penetration with a penetration rate of 3 mm/min was applied during pile penetration. Penetration resistance, \( P \) and penetration depth, \( H \) were measured during the tests. Soil plug height, \( h \) was measured using a scaled-mark string attached to a small weight at the bottom by stopping loading at 10 mm interval as shown in Fig. 5.

Stainless steel piles were used in the experimental work as given in Table 2 and Fig. 6. As the plugged condition may be affected by pile diameters, we used piles with two different outer diameters, \( D \). As inner friction resistance is limited to lower part of the pile tip, the heights of sleeve, \( l \) were designed such that \( l = 10 \) mm, 0.5\( D \), 1.0\( D \) and 2.0\( D \) as given in Table 2.

### 3 RESULTS AND DISCUSSIONS

The most widely used index to describe the degree of plugging of open-ended piles; incremental filling ratio \( (IFR) \) is defined in Eq. 2. \( IFR \) gives the instantaneous plugging state at small penetration depth.

\[
IFR = \frac{\Delta h}{\Delta H} \times 100(\%)
\]  

(2)

Where \( \Delta h \) is the change of soil plug length for penetration depth of \( \Delta H \) (see Fig. 5).

#### Table 2. The details of the model piles

<table>
<thead>
<tr>
<th>Pile notation</th>
<th>Pile type†</th>
<th>Tip thickness, ( t ) (mm)</th>
<th>Sleeve height, ( l ) (mm)</th>
<th>Top thickness, ( t_{top} ) (mm)</th>
<th>Pile outer diameter, ( D ) (mm)</th>
<th>Annular area, ( A_{an} ) (mm(^2))</th>
<th>Area ratio, ( \frac{A_{an}}{\pi D^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{sr}.1-240OE</td>
<td>1.5</td>
<td>240</td>
<td>1.5</td>
<td>30</td>
<td>134.3</td>
<td>0.190</td>
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<tr>
<td>P_{sr}.3-0-10OE</td>
<td>3.0</td>
<td>10</td>
<td>1.5</td>
<td>30</td>
<td>254.5</td>
<td>0.360</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.3-0-30OE</td>
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<td>30</td>
<td>1.5</td>
<td>30</td>
<td>254.5</td>
<td>0.360</td>
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<tr>
<td>P_{sr}.3-0-60OE</td>
<td>3.0</td>
<td>60</td>
<td>1.5</td>
<td>30</td>
<td>254.5</td>
<td>0.360</td>
<td></td>
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<tr>
<td>P_{sr}.2-0-380OE</td>
<td>2.0</td>
<td>380</td>
<td>2.0</td>
<td>50</td>
<td>301.6</td>
<td>0.154</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.4-10OE</td>
<td>4.0</td>
<td>10</td>
<td>2.0</td>
<td>50</td>
<td>578.1</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.4-25OE</td>
<td>4.0</td>
<td>25</td>
<td>2.0</td>
<td>50</td>
<td>578.1</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.4-50OE</td>
<td>4.0</td>
<td>50</td>
<td>2.0</td>
<td>50</td>
<td>578.1</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.4-100OE</td>
<td>4.0</td>
<td>100</td>
<td>2.0</td>
<td>50</td>
<td>578.1</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.0-240CE</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
<td>706.9</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>P_{sr}.0-380CE</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>50</td>
<td>1963.5</td>
<td>1.000</td>
<td></td>
</tr>
</tbody>
</table>

Note: †OE is open-ended, CE is closed-ended, *A is total area covered by outer diameter

#### 3.1 Effects of wall thickness

Figs. 7a and 7b show the results of penetration resistance, \( P \) versus penetration depth, \( H \) for \( D=30 \) and \( 50 \) mm piles respectively. As shown in Figs. 7a and 7b, closed-ended piles produce larger penetration resistance than similar open-ended piles. Theoretically, only a fully plugged open-ended pile (i.e., \( IFR=0\% \)) can produce an equal penetration resistance as a closed-ended pile. Fig. 7a shows that piles with larger tip thickness produce larger penetration resistance (by comparing \( t=1.5 \) and 3.0 mm piles), which can be attributed to the increasing annular area (see Table 2).
Fig. 7b also reveals the same finding (by comparing $t=2.0$ and $4.0$ mm piles) for $D=50$ mm piles.

3.3 Inner frictional resistance

As outer frictional resistance, $Q_{out}$ (see Eq. 3) was found to be 7 and 19 N at 120 and 150 mm depth for $D=30$ and 50 mm piles respectively (assuming 35 degree of soil frictional angle, $\phi, 0.6\phi$ of frictional angle between the pile shaft and soil, $\delta, 0.45$ of coefficient of lateral earth pressure, $k$ according to Tomlinson (2004)), it was ignored in the analysis. $Q_{an}$ was calculated using the area ratio given in Table 2 and $Q_l$ ($Q_l$ is total resistance and equal to $P$) of respective closed-ended piles as given in Eq. 5. Then, $Q_{in}$ was calculated by subtracting $Q_{an}$ from $Q_l$.

$$Q_{out} = Aq$$

Where $A$ is effective surface area of pile shaft and $q$ is unit outer frictional capacity as given in Eq. 4.

$$q = k\sigma \tan \delta$$

Where $k$ is coefficient of lateral earth pressure, $\sigma$ is effective overburden pressure and $\delta$ is frictional angle between the pile shaft and soils.

$$Q_{an,t=3.0} = \frac{A_n}{A_1} Q_{l,D=30}$$

Where $Q_{an,t=3.0}$ is annulus resistance of $t=3.0$ mm piles, $A_n$ is annular area (see Eq. 6), $A_1$ is total area covered by outer diameter, $D$ and $Q_{l,D=30}$ is total resistance of $D=30$ mm closed-ended pile.

$$A_n = \frac{\pi}{4} (D^2 - d^2)$$

Where $d$ is pile inner diameter.

Figs. 8a and 8b show the results of $Q_n$ for $D=30$ and 50 mm piles respectively. As shown in Fig. 8a for $D=30$ mm piles, $Q_n$ is independent of the sleeve length, $l$. However, as shown in Fig. 8b for $D=50$ mm piles, $Q_n$ is dependent of $l$. Figs. 9a and 9b show $Q_n$ and $Q_{an}$ as percentage of $Q_l$ for $D=30$ and 50 mm piles respectively. As shown in Fig. 9a, $D=30$ mm piles produce approximately 50% of $Q_l$ by $Q_{an}$ regardless of the value of $l$. In contrast, in $D=50$ mm piles (see Fig. 9b), $Q_n$ is a linear function of $l$ and only the pile with 2$D$ of $l$ produces as large as 50% of $Q_l$ by $Q_{an}$. Fig. 9 also shows that the pile with 10 mm of $l$ $(D=50$ mm) produces only 10% of $Q_l$ by $Q_{in}$ in contrast to 50% by the $D=30$ mm pile. Therefore, we can suggest that smaller sleeve height is sufficient in smaller diameter piles to produce significant inner frictional resistance, while higher sleeve height is required in larger diameter piles to produce large $Q_l$ by $Q_{in}$. Also, we can conclude that $Q_n$ is dependent of $l$ for larger diameter piles while it is independent of $l$ for smaller diameter piles.

Figs. 10a and 10b show soil plug height, $h$ versus penetration depth, $H$ for $D=50$ and 50 mm piles respectively. In both cases, the straight piles (i.e., no sleeve or $l$ is equal to pile length) show that the penetration is closer to unplugged state than the piles with a sleeve. Figs. 11a and 11b show the results of IFR from $D=30$ and 50 mm piles respectively. The results of
IFR showed that \(D=30\) mm piles are penetrated under higher degree of plugging than \(D=50\) mm piles. As shown in Fig. 11a for \(D=30\) mm piles, \(d=24\) mm piles (\(d\) is pile inner diameter) penetrated under 40-70% of IFR while \(d=27\) mm pile penetrated under 80% of IFR at 120 mm penetration depth (i.e., \(4D\)), which suggest that smaller diameter piles penetrate under higher degree of plugging. Fig. 11b, from \(D=50\) mm piles, also suggest that the piles with smaller \(d\) have higher degree of plugging (by comparing \(d=42\) and 46 mm piles). The results from Fig. 11b also suggest \(l\) affects degree of plugging here, not like in \(D=30\) mm piles. Fig. 11b also reveals that higher \(l\) results in higher degree of plugging (by comparing \(l=10\), 25, 50 and 100 mm piles). The results from \(D=30\) mm piles suggest that shorter \(l\) (i.e., \(l=10\) mm) is sufficient to produce considerable degree of plugging. However, the results from \(D=50\) mm piles suggest that IFR is affected by \(l\). Therefore, we can conclude that although \(l\) of smaller diameter piles is not important for IFR, that is important for larger diameter piles.

**Fig. 8.** Inner frictional resistance for (a) \(D=30\) mm and (b) \(D=50\) mm piles

![Inner frictional resistance](image)

**Fig. 9.** \(Q_a\) and \(Q_m\) as a percentage of \(Q_t\) for (a) \(D=30\) mm and (b) \(D=50\) mm piles

4 CONCLUSIONS

In this paper, the effects of pile diameters, tip thicknesses and sleeve heights of open-ended piles on the bearing capacity, particularly inner frictional resistance were discussed using laboratory scale model piles. The results showed that the bearing capacity increases with tip thickness, \(t\), which can be attributed to the increasing annular area. They also showed that soil plug length, \(h\) is dependent of sleeve heights, \(l\) for larger diameter piles, while it is independent for smaller diameter piles. The results also showed that the penetration of the straight piles (i.e., no sleeve) is closer to unplugged state than the piles with a sleeve. While inner frictional resistance, \(Q_m\) is independent of \(l\) for smaller diameter piles, it is dependent of \(l\) for larger diameter piles, where \(Q_m\) increases linearly with \(l\). The results of \(Q_m\) suggested that as large as 50% of \(Q_t\) (\(Q_t\) is total resistance) is contributed by \(Q_m\) even with a small \(l\) (e.g., 10 mm) for smaller diameter piles, while \(Q_m\) in larger diameter piles increases with \(l\) and requires 2\(D\) of \(l\) to produce as large as 50% of \(Q_t\) by \(Q_m\).

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Fig. 10 Soil plug height vs. penetration depth from (a) D=30 and (b) D=50 mm piles

Fig. 11. IFR vs. penetration depth from (a) D=30 and (b) D=50 mm piles

REFERENCES