The effects of pile diameter and sleeve height on incremental filling ratio (IFR)

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ABSTRACT

The bearing capacity of an open-ended pile depends largely on the degree of soil plugging. Many factors including pile diameter, relative density and the end conditions of piles may influence the degree of soil plugging. The degree of soil plugging is mainly described by the incremental filling ratio (0 and 100% of it imply a fully-plugged and unplugged state respectively). In this paper, the effects of pile diameter and height of an inner sleeve attached to the base of an open-ended pile on the incremental filling ratio are discussed. The experiments were conducted on a medium-dense sandy ground using small-scale model piles. The experimental results suggest that the bearing capacity is influenced by the sleeve height for 50 mm diameter piles while it is independent for 30 mm diameter piles, probably due to the influence on the inner frictional resistance. The results also indicate that a longer sleeve produces a shorter soil plug regardless of the pile diameter. The results of the incremental filling ratio show that the penetration of non-sleeved piles is closer to the unplugged state than the sleeved piles. The results of the IFR also reveal that the degree of soil plugging is affected by the sleeve height of a slightly larger diameter piles of 50 mm while it is independent for 30 mm diameter piles. While the degree of soil plugging remains same after a depth of roughly 1D penetration (D is pile outer diameter) for 50 mm diameter piles, it linearly increases (i.e., decreasing IFR) with the penetration for 30 mm diameter piles.

Keywords: bearing capacity, incremental filling ratio, inner sleeve, open-ended pile, pile diameter, soil plugging

1 INTRODUCTION

Open-ended piles are used extensively in offshore deep foundations. Previous studies have shown that the behavior of open-ended piles is different from closed-ended piles (Paikowsky and Whitman, 1990; Leland, 1991; Lee et al., 2003; Xu et al., 2008). A short open-ended pile produces a smaller bearing capacity than a closed-ended pile. However, a long open-ended pile can produce a similar bearing capacity as a closed-ended pile due to a large inner frictional resistance mobilized between the inner pile shaft and inner soil (Lehane and Randolph, 2002). The bearing capacity of an open-ended pile consists of three components as given in Eq. 1. It is clear from Eq. 1 that the bearing capacity of an open-ended pile depends largely on the plug capacity (see Eq. 2), which is influenced by the degree of soil plugging.

\[ Q_u = Q_a + Q_o + Q_{plug} \]  

(1)

Where \( Q_u \) is bearing capacity, \( Q_a \) is annulus resistance, \( Q_o \) is outer frictional resistance and \( Q_{plug} \) is plug resistance (see Eq. 2).

Where \( Q_{plug} = \min(Q_a, Q_b) \)  

(2)

Where \( Q_{plug} \) is plug resistance, \( Q_a \) is inner frictional resistance and \( Q_b \) is base resistance.

When an open-ended pile is driven into a soil, underneath soil penetrates into the pile and generates a soil plug. The bearing capacity of it depends on the degree of soil plugging. A fully-plugged open-ended pile behaves similar to a closed-ended pile. However, most piles in practice are driven under partially-plugged mode (Tolmison, 2004; Gudavalli et al., 2013). Due to a lack of inner frictional resistance, an unplugged open-ended pile produces a much smaller bearing capacity than its fully- or partially-plugged counterparts. Many factors of pile installation methods, ground conditions and geometrical conditions of the piles can affect the mechanism of the soil plugging (Paik and Salgado, 2004; Henke and Grabe, 2008; 2013). Previous studies have also reported that a loose ground condition leads to a higher plugging condition (Paik and Salgado, 2003; Paik et al., 2003).

Some design methods such as UWA method (Lehane et al., 2005) and HKU method (Yu and Yang,
2012) relate the incremental filling ratio to the evaluation of the bearing capacity of open-ended piles explicitly or implicitly. Therefore, the evaluation of incremental filling ratio is important for open-ended piles. However, the effects of the inner sleeves attached to the pile base on the mechanism of soil plugging have hardly been studied in past. Therefore, in this research, the behaviour of inner-sleeved open-ended piles was studied, particularly discussing the effects of pile diameter and sleeve height on the incremental filling ratio.

2 METHODOLOGY

The model ground was prepared in a soil tank with the dimension of 300 mm inner diameter and 250 mm height as shown in Fig. 1a. The bearing house fitted on the top cover was designed to maintain the verticality of the piles during the pile installation and loading. The loading apparatus is shown in Fig. 1b. Silica sand was used to prepare the model ground. The physical properties and particle size distribution of silica sand are given in Table 1 and Fig. 2 respectively. The density tests were conducted according to JIS (2009). The model ground was prepared with a 60% of relative density. The required relative density was achieved by pouring the sand to the soil tank through a tube of 30 mm diameter from a constant height (i.e., air pluviation method).

| Property                              | Result  |
|---------------------------------------|---------|
| Mean diameter, $D_{50}$ (mm)          | 0.590   |
| Coefficient of uniformity, $C_u$      | 1.446   |
| Coefficient of curvature, $C_c$       | 0.926   |
| Particle density, $\rho_s$ (kg/m$^3$) | 2647    |
| Maximum dry density, $\rho_d,max$ (kg/m$^3$) | 1567    |
| Minimum dry density, $\rho_d,min$ (kg/m$^3$) | 1278    |
| Maximum void ratio, $e_{max}$         | 1.072   |
| Minimum void ratio, $e_{min}$         | 0.689   |

The static penetration with a penetration rate of 3 mm/min was applied during the pile penetration. The penetration resistance and penetration depth were measured during the loading. The penetration resistance was measured at the pile head (see Fig. 1b). Therefore, a small consistent friction (e.g., less than 2 N) between the pile and bearing house is included in the measurement. The displacement of the piles was also measured at the pile head using an external displacement transducer (see Fig. 1b). Soil plug height was measured using a scaled-mark string connected to a small weight at the bottom by stopping the loading at 10 mm intervals as shown in Fig. 3. After the loading is stopped, the string is inserted into the pile and then the soil plug height is measured using the scale.

Stainless steel piles were used in the experimental works. Five and four open-ended piles of 50 and 30 mm diameters respectively were used for the experiments as given in Table 2. In the pile notation of $P_{30}-3.0-10$ (see Table 2), 30 is pile outer diameter, 3.0 is wall thickness, and 10 is pile length.
at the pile tip and 10 is sleeve height. The non-sleeved piles of \( P_{50}-2.0-380 \) and \( P_{30}-1.5-240 \) have 2 and 1.5 mm of wall thicknesses throughout the pile length whereas the sleeved piles have different wall thicknesses at the sleeve and above it. As inner friction resistance is limited to the lower part of a pile (Kikuchi, 2010), the height of the sleeve was designed such that it is equal to 10 mm, 0.5\( D \), 1.0\( D \) or 2.0\( D \) (\( D \) is pile outer diameter) as given in Table 2.

![Diagram of sleeve height](image)

**Fig. 3.** The measurement method of soil plug height.

| Pile notation | Tip thickness, \( t \) (mm) | Sleeve height, \( l \) (mm) | Pile inner diameter, \( d \) (mm) | Annular area, \( A_{\text{ann}} \) (mm\(^2\)) | Area ratio*, \( A_{\text{cor}}/A_{\text{tot}} \) |
|---------------|-----------------------------|-----------------------------|-----------------------------|------------------------------------------|----------------------------------|
| \( P_{50}-1.5-240 \) | 1.5                         | 24                          | 27                          | 134.3                                    | 0.190                             |
| \( P_{50}-3.0-10 \)  | 3.0                         | 10                          | 24                          | 254.5                                    | 0.360                             |
| \( P_{50}-3.0-30 \)  | 3.0                         | 30                          | 24                          | 254.5                                    | 0.360                             |
| \( P_{50}-3.0-60 \)  | 3.0                         | 60                          | 24                          | 254.5                                    | 0.360                             |
| \( P_{50}-2.0-380 \) | 2.0                         | 380                         | 46                          | 301.6                                    | 0.154                             |
| \( P_{30}-4.0-10 \)  | 4.0                         | 10                          | 42                          | 578.1                                    | 0.294                             |
| \( P_{30}-4.0-25 \)  | 4.0                         | 25                          | 42                          | 578.1                                    | 0.294                             |
| \( P_{30}-4.0-50 \)  | 4.0                         | 50                          | 42                          | 578.1                                    | 0.294                             |
| \( P_{30}-4.0-100 \) | 4.0                        | 100                          | 42                          | 578.1                                    | 0.294                             |

Note: *\( A_{\text{tot}} \) is total area covered by outer diameter

### 3 RESULTS AND DISCUSSION

The incremental filling ratio (IFR) is defined in Eq. 3. The IFR gives the instantaneous plugging state at small penetration depth.

\[
IFR = \frac{\Delta h}{\Delta H} \times 100(\%) \tag{3}
\]

Where \( \Delta h \) is the change of soil plug length for penetration depth of \( \Delta H \) (see Fig. 3).

The IFR has been defined for non-sleeved piles (Paikowsky et al., 1989; Paik and Salgado, 2003). Therefore, the measured soil plug height of the sleeved piles should be corrected to evaluate the IFR. The measured soil plug height was corrected then as given in Eq. 4 assuming that the soil volume of a sleeved pile is equal to its virtual non-sleeved pile.

\[
h_{\text{cor}} = \left( \frac{d}{d_{\text{cor}}} \right)^2 h
\tag{4}
\]

Where \( h_{\text{cor}} \) is the corrected soil plug height, \( d \) is pile inner diameter, \( d_{\text{cor}} \) is pile inner diameter of its respective non-sleeved pile and \( h \) is the measured soil plug height.

Figs. 4 and 5 show the soil plug height versus penetration depth for 50 and 30 mm diameter piles respectively. The IFRs were then evaluated using the corrected soil plug height given by Eq. 4. Figs. 4a and 4b show the measured and corrected soil plug height according to Eq. 4 respectively for 50 mm diameter piles. In both figures, the non-sleeved pile (i.e., \( P_{50}-2.0-380 \)) penetrates under the unplugged state. Although the measured soil plug height of the sleeved piles are approximately same for 50 mm piles (see Fig. 4a), Fig. 4b indicates that a pile with a longer sleeve produces a shorter soil plug. A shorter soil plug might be interpreted as a higher degree of soil plugging. The same observations can be seen for 30 mm diameter piles as well (see Figs. 5a and 5b). Therefore, we can conclude that a longer sleeve of an open-ended pile produces a shorter soil plug regardless of the pile diameter.

The degree of soil plugging should be described by the incremental filling ratio as it indicates the instantaneous plugging condition with the penetration depth. Figs. 6 and 7 show the incremental filling ratio versus penetration depth for 50 and 30 mm diameter piles respectively. Figs. 6a and 6b show the original and corrected incremental filling ratios calculated using the corrected soil plug height respectively for 50 mm diameter piles. The results clearly indicate that the non-sleeved pile penetrates closer to the unplugged state with roughly a 100% of IFR as seen in Figs. 6a and 6b. The results also show that the sleeved piles penetrate under the partially-plugged state with a 65-90% of IFR as seen in Figs. 6a and 6b. The results also depict that the corrected incremental filling ratio indicates that plugging condition more accurately at the shallow penetration depth (or the penetration is equal to the length of the sleeve height). Fig. 6b also indicates that a pile with a longer sleeve (i.e., more than 2\( D \); \( D \) is pile outer diameter) produces a considerable degree of soil plugging (e.g., 60-75% of IFR) whereas a pile with a shorter sleeve (i.e., less than 1\( D \)) produces a negligible degree of soil plugging (e.g., 80-90% of IFR).

The results also suggest the degree of soil plugging remains more or less same (i.e., 70-85% of IFR) after a penetration of roughly 50 mm (i.e., which is equal to 1\( D \)).
Figs. 7a and 7b show the original and corrected incremental filling ratios respectively for 30 mm diameter piles. We can again observe here that the non-sleeved pile (i.e., \( P_{30}-1.5-240 \)) penetrates closer to the unplugged state than the sleeved piles same as in 50 mm diameter piles. The results in Figs. 7a and 7b also indicate that 30 mm diameter piles penetrate under a slightly higher degree of soil plugging by producing slightly smaller values of IFR than 50 mm diameter piles (i.e., 50-65% for 30 mm diameter piles over 65-85% of IFR observed for the sleeved piles of 50 mm diameter). However, on contrast to 50 mm diameter piles, the sleeve height of 30 mm diameter piles does not affect the degree of soil plugging. The results also indicate that the degree of soil plugging increases with the penetration for 30 mm diameter piles contrast to 50 mm diameter piles, where the degree of soil plugging remains same after a penetration of roughly 1D depth (\( D \) is pile outer diameter).

Figs. 8a and 8b show the penetration resistance versus penetration depth for 50 and 30 mm diameter piles respectively. Figs. 8a and 8b show that the closed-ended piles (i.e., \( P_{50}-0.0-380 \) and \( P_{30}-0.0-240 \)) produces a larger penetration resistance than the respective open-ended piles, which should be expected for partially-opened piles. Theoretically, only a fully-plugged open-ended pile can produce a similar penetration resistance to a closed-ended pile. As shown in Fig. 8a, in the four 50 mm diameter open-ended piles of \( t=4.0 \) mm (\( t \) is wall thickness at the pile tip), the penetration resistance increases with sleeve height. Fig. 8a clearly shows that piles with a higher sleeve height produce a larger penetration resistance. As annular area is equal for these piles (see Table 2), the annulus resistance can be assumed to be equal for these piles. Therefore, the difference in the penetration resistance can be attributed to the difference in inner frictional resistance. On contrast, 30 mm diameter open-ended piles (see Fig. 8b) indicate that the sleeve height does not influence the bearing capacity. Figs. 8a and 8b also indicate that the thinner-walled piles (i.e., \( P_{50}-2.0-380 \) and \( P_{30}-1.5-240 \)) produce smaller penetration resistance than the respective thick-walled piles.
CONCLUSIONS

In this paper, the effects of pile diameter and sleeve height on the incremental filling ratio (IFR) of open-ended piles are discussed using the experimental results of small-scale model piles. The experimental results suggest that the bearing capacity is influenced by the sleeve height for 50 mm diameter piles while it is independent for 30 mm diameter piles. The results also indicate that a longer sleeve of an open-ended pile produces a shorter soil plug regardless of the pile diameter. The results of the incremental filling ratio show that the penetration of non-sleeved piles is closer to the unplugged state than the sleeved piles. The results of the IFR also reveal that the degree of soil plugging is affected by the sleeve height of a slightly larger diameter piles of 50 mm while it is independent for 30 mm diameter piles. While the degree of soil plugging remains same after a depth of roughly 1D penetration (D is pile outer diameter) for 50 mm diameter piles, it linearly increases (i.e., decreasing IFR) with the penetration for 30 mm diameter piles.
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