Influence of relative density on the degree of soil plugging of pipe piles driven in sandy soils

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ABSTRACT

Bearing capacity of open-ended piles installed in sandy grounds depends heavily on the degree of soil plugging. A fully-plugged pile generally produces a bearing capacity similar to a closed-ended pile. In this paper, soil plugging behavior of inner-sleeved open-ended piles driven in sandy soils is discussed. The piles were penetrated in dense and loose sands. The degree of soil plugging is discussed using a modified version of incremental filling ratio. The results suggest that loose sand produces a relatively higher degree of soil plugging. The results also indicate that the open-ended piles penetrated in dense sand produce larger penetration resistance than loose sand. The results further suggest that a pile of a taller sleeve produces a larger resistance than shorter counterparts in both loose and dense sands. The results also indicate that a pile of a very short sleeve (e.g., 10mm) produces very small or no inner frictional resistance. The results also indicate that the inner frictional resistance develops rapidly with the sleeve length in dense sand than loose sand. Therefore, we recommend a use of a tall sleeve in loose sand while relatively a short sleeve in dense sand for effective use of the inner sleeve in mobilising inner frictional resistance.

Keywords: bearing capacity, incremental filling ratio, inner sleeve, pipe pile, soil plugging

1 INTRODUCTION

In recent offshore projects such as seaports and airports, steel open-ended piles have extensively been used mainly due to relative easiness in penetration. A short open-ended pile produces relatively smaller bearing capacity than its equivalent closed-ended pile (Naury and Tirant 1983). However, many open-ended piles installed in offshore constructions can produce a bearing capacity similar to their equivalent closed-ended piles due to large inner frictional resistance mobilised between the inner pile shaft and inner soil (Lehane and Randolph 2002). The difference in bearing capacity between open- and closed-ended piles can be attributed to various aspects such as piles’ geometrical conditions, installation methods, ground conditions and so on.

The bearing capacity of an open-ended pile consists of three components such as annulus resistance, outer frictional resistance and plug resistance (see Eq. 1 and Fig. 1). The outer frictional resistance is mobilised between the pile outer shaft and outer soil. The plug resistance is the minimum of base resistance or inner frictional resistance. We have the least knowledge on the plug resistance among the individual resistances due to a lack of knowledge on the mechanisms of soil plugging.

\[ Q_i = Q_{an} + Q_{out} + Q_{plug} \]  

Where \( Q_i \) is bearing capacity, \( Q_{an} \) is annulus resistance, \( Q_{out} \) is outer frictional resistance and \( Q_{plug} \) is plug resistance.

![Fig. 1. The components of the bearing capacity of an open-ended pile](http://doi.org/10.3208/jgssp.v05.007)
When an open-ended pile is driven into a sandy soil, underneath sand penetrates into the pile and generate a soil plug. As penetration continues, plug resistance develops and may prevent further soil intrusion. Generally, if a small diameter open-ended pile is penetrated to a greater depth under fully-plugged mode, it behaves similar to a closed-ended pile. In contrast, an open-ended pile driven under fully coring (or unplugged) mode produces much smaller bearing capacity than its similar closed-ended pile. However, most piles in practice are driven under partially-plugged mode (Kikuchi 2011, Jeong et al. 2015). Although a tall soil plug is developed in an unplugged open-ended pile, it may produce a small inner frictional resistance due to the upward movement of the soil plug relatively to the pile. The soil plug settles with the pile as an intact body in a fully-plugged pile during pile installation. More details of the penetration modes of open-ended piles can be found in Kumara et al. (2016).

Various aspects of pile installation methods, ground conditions and geometrical conditions of the open-ended piles can influence the degree of the soil plugging (Paik and Salgado 2004, Schneider et al. 2008). The lack of knowledge on the mechanisms of soil plugging has led various design methods adopting different design parameters in the evaluation of bearing capacity for open-ended piles (Guo and Yu 2016). In many laboratory (and also field) experiments, non-sleeved open-ended piles have been used to discuss various issues of inner frictional resistance and soil plugging. In this paper, the effects of ground density on the behaviour of inner-sleeved open-ended piles are discussed, particularly highlighting the aspects of soil plugging.

2 METHODOLOGY

The model ground was prepared in a soil tank with the dimension of 300mm inner diameter and 300mm height as shown in Fig. 2(a). The air pluviation method was adopted to prepare the sandy ground. Silica sand was used to prepare the model ground. The model ground was prepared with dense and loose sands by 60 and 30% of relative densities respectively. The loose ground was prepared by pouring sand into the soil tank by maintaining a zero height between the ground surface and soil pouring from a tube of 30mm diameter. The dense ground was prepared by maintaining a 30mm height from the tube. The physical properties and particle size distribution of silica sand are given in Fig. 3. The soil tank is equipped with a top cover, which is fitted with a bearing house. The bearing house was designed to maintain the verticality of the piles during pile installation. The loading apparatus is shown in Fig. 2(b). The static penetration with a penetration rate of 3mm/min was applied during pile installation. The total resistance and penetration depth were measured using a load cell and external displacement transducer respectively during pile penetration.

Stainless steel piles were used in the experiments. As given in Table 1, in total five open- and one closed-ended piles of 50 mm outer diameter were used.
Figs. 4(a)-(c) show schematic diagrams of non-sleeved open-ended pile, sleeved open-ended pile and closed-ended pile respectively. The open-ended piles were designed with an inner sleeve at the pile tip as shown in Fig. 4(b). The length of the sleeve is designed as 10 mm (the shortest sleeve), 0.5, 1.0 and 2.0 \( D \) (\( D \) is pile outer diameter). In the pile notation of \( P_{50}-3-100 \) (see Table 1), 50 is pile outer diameter (in mm), 3 is wall thickness at the pile base (in mm) and 100 is the sleeve length (in mm).

Table 1. The geometrical properties of the piles.

| Pile notation | Pile type | Tip thickness, \( t \) (mm) | Sleeve length, \( l \) (mm) | Top thickness, \( t_{top} \) (mm) | Annular area, \( A_{\text{ann}} \) (mm\(^2\)) | Area ratio, \( A_{\text{ann}}/A_{\text{t}} \) |
|---------------|----------|----------------|----------------|----------------|----------------------|------------------------|
| \( P_{50}-3-380 \) | OE | 3 | 0 | 3.0 | 443 | 0.226 |
| \( P_{50}-3-100 \) | OE | 3 | 100 | 1.5 | 443 | 0.226 |
| \( P_{50}-3-50 \) | OE | 3 | 50 | 1.5 | 443 | 0.226 |
| \( P_{50}-3-25 \) | OE | 3 | 25 | 1.5 | 443 | 0.226 |
| \( P_{50}-3-10 \) | OE | 3 | 10 | 1.5 | 443 | 0.226 |
| \( P_{50}-0-380 \) | CE | N/A | N/A | N/A | 1963.5 | 1.000 |

Note: †OE and CE are open- and closed-ended piles, *\( A_{\text{t}} \) is total area covered by pile outer diameter

Fig. 4. (a) A schematic diagram of a (a) non-sleeved and (b) sleeved open-ended pile, and (c) closed-ended pile (\( l \) is sleeve length and \( t \) is wall thickness at the pile base)

Soil plug height is used to discuss the degree of soil plugging by the incremental filling ratio. In this study, we measured the soil plug heights in all the experiments. The measurement method is illustrated in Fig. 5. First, we stopped loading at each 25 mm penetration depth. After unloading, the pile and load cell is disconnected. Then, we shifted the soil tank slightly away from the loading road using the sliding plate on which the soil tank is placed on. Then, we inserted the scale-marked string onto the soil plug as shown in Fig. 5. The scale is marked at 1 mm interval. The bottom of the string is connected with a small weight such that we can judge when it touches the top of the soil plug. After measuring the soil plug height, the loading was again started. The procedure was continued until the full penetration depth.

![Fig. 5. A schematic diagram of the measurement method of soil plug height (\( h \) is soil plug height and \( H \) is penetration depth)](image)

3 RESULTS AND DISCUSSION

3.1 The soil plugging

The measured soil plug height was modified to take account the sleeved part of an open-ended pile. The modified soil plug height within the sleeved part of an open-ended pile is evaluated using Eq. 2. More details of it can be found in Kumara et al. (2015). Figs. 6(a) and (b) show the variation of the modified soil plug height versus penetration depth in dense and loose sands respectively. The results suggest the non-sleeved pile (i.e., \( P_{50}-3-380 \)) behaves near to the unplugged state. It also indicates that a taller sleeve encourages the soil plugging than a shorter sleeve in both dense and loose sands. On average, the piles in loose sand produce shorter soil plugs. A shorter soil plug generally implies a higher degree of soil plugging.

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

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

The modified incremental filling ratio was evaluated using the modified soil plug height as given in Eq. 3. Figs. 7(a) and (b) show the modified incremental filling ratio versus penetration depth in dense and loose sands respectively. The incremental filling ratio describes the degree of soil plugging better than the plug length ratio due to discontinuous nature of soil plugging particularly in a deep penetration. As the piles were penetrated into
a relatively shallow depth in this study, both incremental filling ratio and plug length ratio would describe the behaviour of soil plugging similarly. Figs. 7(a) and (b) indicate that $IFR_{mod}$ is 85-100 and 75-85% for dense and loose sands respectively. Therefore, we can clearly see here that loose sand produces relatively higher degree of soil plugging (i.e., smaller values of $IFR$).

$$IFR_{mod} = \frac{\Delta h_{mod}}{\Delta H} \times 100(\%)$$ \hspace{1cm} (3)

Where $\Delta h_{mod}$ is the change in the modified soil plug height for penetration depth of $\Delta H$ (see Fig. 5).

Fig. 6. Modified soil plug height versus penetration depth in (a) dense and (b) loose sand

### 3.2 Penetration resistance

Figs. 8(a) and (b) show the total resistance versus penetration depth for dense and loose sands respectively. Figs. 8(a) and (b) clearly indicate that the dense soil produces a higher total penetration resistance. The results also indicate that the non-sleeved pile (i.e., $P_{50-3-380}$) produces the largest total resistance, which suggest that the sleeve length of 100mm (i.e., $2D$ distance; $D$ is pile outer diameter) is not sufficient to mobilise the full inner frictional resistance. In dense sand, 100mm sleeve pile produces a larger resistance than other sleeved piles as shown in Fig. 8(a). The pile of the shortest sleeve (i.e., $P_{50-3-10}$) produces the smallest resistance. The piles of intermediate sleeve lengths produce a resistance in between the two piles. In the loose sand, the piles of 50 and 100mm sleeve lengths (i.e., $1$ and $2D$ distance) produce approximately similar resistance while the piles of 10 and 25mm sleeve lengths produce smaller resistance than the piles of a taller sleeve as shown in Fig. 8(b). We can observed here that a pile of a taller sleeve produces a larger resistance than a pile of a shorter sleeve.

Fig. 7. Modified incremental filling ratio versus penetration depth in (a) dense and (b) loose sand

#### 3.3 Inner frictional resistance

Outer frictional resistance can be calculated using Eq. 4. The coefficient of lateral earth pressure, $K_0$ in Eq. 5 is taken as 0.50 and 0.45 for loose and dense sands respectively considering the average value proposed by Tomlinson (2004). The interface friction angle between the inner pile shaft and soil, $\delta$ (see Eq. 5) is also taken as the average value (i.e., $0.6\phi$, $\phi$ is soil internal friction angle) proposed by Tomlinson (2004). Then, the $\delta$ becomes 18 and 21 degree for loose and dense sands respectively.

$$Q_{out} = A q_{out}$$ \hspace{1cm} (4)

Where $Q_{out}$ is outer frictional resistance, $A$ is surface area of pile shaft and $q_{out}$ is unit outer frictional resistance as given in Eq. 5.
Where $K_h$ is coefficient of lateral earth pressure, $\sigma_v$ is effective overburden pressure and $\delta$ is interface friction angle between pile shaft and soil.

\[ q_{\text{out}} = K_h \sigma_v \tan \delta \]  \hspace{1cm} (5)

Fig. 8. Total resistance versus penetration depth in (a) dense and (b) loose sand

Annulus frictional resistance of the open-ended piles was calculated using the method reported in Kumara et al. (2016) as given in Eq. 6. Then, the inner frictional resistance of an open-ended pile can be calculated as given in Eq. 8.

\[ Q_{\text{an}} = \frac{A_{\text{an}}}{A_t} Q_{\text{b,CE}} \]  \hspace{1cm} (6)

Where $Q_{\text{an}}$ is annulus resistance, $A_{\text{an}}$ is annular area (see Eq. 7), $A_t$ is total area covered by pile outer diameter and $Q_{\text{b,CE}}$ is base resistance of a closed-ended pile of the same diameter.

\[ A_{\text{an}} = \frac{\pi}{4}(D^2 - d^2) \]  \hspace{1cm} (7)

Where $A_{\text{an}}$ is annular area, $D$ and $d$ are pile outer and inner diameters respectively.

\[ Q_{\text{in}} = Q_t - (Q_{\text{out}} + Q_{\text{an}}) \]  \hspace{1cm} (8)

Where $Q_{\text{in}}$ is inner frictional resistance, $Q_t$ is total resistance, $Q_{\text{out}}$ is outer frictional resistance and $Q_{\text{an}}$ is annulus resistance.

Figs. 9(a) and (b) show the inner frictional resistance versus penetration depth in dense and loose sands respectively. As shown in Figs. 9(a) and (b), inner frictional resistance increases with the relative density. In both dense and loose sands, the non-sleeved pile (i.e., $P_{50-3-380}$) produces the largest inner frictional resistance while the pile of a shortest sleeve (i.e., $P_{50-3-10}$) produces the smallest inner frictional resistance. Therefore, it is clear that a sufficiently lengthily sleeve is needed to produce a large inner frictional resistance. The results also suggest that the inner frictional resistance increases with the penetration depth. Therefore, we can understand that a large penetration depth is required to produce a large inner frictional resistance. This is why open-ended piles are more popular in offshore constructions where long length open-ended piles penetrated into deeper ground can produce similar bearing capacity as closed-ended piles. The results also suggest that the non-sleeved pile and the pile of 2D sleeve length ($D$ is pile diameter) may produce a closer inner frictional resistance at deeper penetration depth in dense sand than loose sand.

Fig. 9. Inner frictional resistance versus penetration depth in (a) dense and (b) loose sand
Fig. 10 shows the inner frictional resistance versus sleeve length in dense and loose sands. Fig. 10 reveals that dense sand is more effective in increasing inner frictional resistance, $Q_{in}$ with a relatively short sleeve as $Q_{in}$ increases rapidly in dense sand up to 100mm of a sleeve length. Thereafter, its increasing rate reduces compared to loose sand. In contrast, $Q_{in}$ increases with the sleeve height until the full sleeve length (i.e., 380mm) in loose sand. Therefore, we can recommend a use of a long sleeve in loose sand while relatively short sleeve in dense sand for effective use of the inner sleeve.

![Graph](image)

**Fig. 10. Inner frictional resistance versus sleeve length ($D_r$ is relative density)**

### 4 CONCLUSIONS

The open-ended piles penetrated in dense sand produce larger resistance than loose sand. A pile of a taller sleeve produces a larger resistance than a pile of a shorter sleeve in both dense and loose sands. The non-sleeved pile produces the largest inner frictional resistance, and the gap between it and the intermediate-sleeved piles reduces when the ground condition becomes denser. The results also suggest a pile of a very shorter sleeve (e.g., 10mm) produces very small or no inner frictional resistance. The results of inner frictional resistance versus sleeve length suggest that the inner frictional resistance develops rapidly with the sleeve height in a dense sand than loose sand. Therefore, we recommend a use of long sleeve in loose sand while relatively short sleeve in dense sand for effective use of the inner sleeve in mobilising inner frictional resistance. The behaviour of soil plugging was discussed using the incremental filling ratio. They were calculated using a modified version to reflect the sleeved part of open-ended piles. The results suggest that the piles penetrated under partially-plugged state, being closer to unplugged state than fully-plugged state. The results also suggest that loose sand produces relatively higher degree of soil plugging.

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### REFERENCES

1. Guo, Y. and Yu, X.B. (2016): Design and analyses of open-ended pipe piles in cohesionless soils, Frontiers of Structural and Civil Engineering, 10(1), 22-29.
2. Jeong, S., Ko, J., Won, J. and Lee, K. (2015): Bearing capacity analysis of open-ended piles considering the degree of soil plugging, Soils and Foundations, 55(5), 1001-1014.
3. Kikuchi, Y. (2011): Mechanism of inner friction of an open-ended pile, Proceedings of 3rd IPA International Workshop (Press-in Engineering 2011), Shanghai, October, 65-83.
4. Kumara, J.J., Kikuchi, Y. and Kurashina, T. (2015): Effective length of the soil plug of inner-sleeved open-ended piles in sand, Journal of GeoEngineering, 10(3), 75-82.
5. Kumara, J.J., Kikuchi, Y. and Kurashina, T. (2016): Effects of the lateral stress on the inner frictional resistance of pipe piles driven into sand, International Journal of Geo-Engineering, 7(1), 1-14.
6. Lehane, B.M. and Randolph, M.F. (2002): Evaluation of a minimum base resistance for driven pipe piles in siliceous sand, Journal of Geotechnical and Geoenvironmental Engineering, 128(3), 198-205.
7. Nauroy, J.F. and Tirant, L.P. (1983): Model tests of piles in calcareous sands, Proceedings of Geotechnical Practice in Offshore Engineering, Austin, 356-369.
8. Paik, K. and Salgado, R. (2004): Effect of pile installation method on pipe pile behavior in sands, Geotechnical Testing Journal, 27(1), 11-22.
9. Schneider, J.A., Xu, X. and Lehane, B.M. (2008): Database assessment of CPT-based design methods for axial capacity of driven piles in siliceous sands, Journal of Geotechnical and Geoenvironmental Engineering, 134(9), 1227-1244.
10. Tomlinson, M.J. (2004): Pile Design and Construction Practice, E & FN Spon, London, England.