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# Effects of pile geometry on bearing capacity of open-ended piles driven into sands

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**Abstract.** Bearing capacity of open-ended piles depends largely on inner frictional resistance, which is influenced by the degree of soil plugging. While a fully-plugged open-ended pile produces a bearing capacity similar to a closed-ended pile, fully coring (or unplugged) pile produces a much smaller bearing capacity. In general, open-ended piles are driven under partially-plugged mode. The formation of soil plug may depend on many factors, including wall thickness at the pile tip (or inner pile diameter), sleeve height of the thickened wall at the pile tip and relative density. In this paper, we studied the effects of wall thickness at the pile base and sleeve height of the thickened wall at the pile tip on bearing capacity using laboratory model tests. The tests were conducted on a medium dense sandy ground. The model piles with different tip thicknesses and sleeve heights of thickened wall at the pile tip were tested. The results were also discussed using the incremental filling ratio and plug length ratio, which are generally used to describe the degree of soil plugging. The results showed that the bearing capacity increases with tip thickness. The bearing capacity of piles of smaller sleeve length (e.g., $\leq 1D$; $D$ is pile outer diameter) was found to be dependent on the sleeve length, while it is independent on the sleeve length of greater than a $1D$ length. We also found that the soil plug height is dependent on wall thickness at the pile base. The results on the incremental filling ratio revealed that the thinner walled piles produce higher degree of soil plugging at greater penetration depths. The results also revealed that the soil plug height is dependent on sleeve length of up to $2D$ length and independent beyond a $2D$ length. The piles of a smaller sleeve length (e.g., $\leq 1D$) produce higher degree of soil plugging at shallow penetration depths while the piles of a larger sleeve length (e.g., $\geq 2D$) produce higher degree of soil plugging at greater penetration depths.

**Keywords:** bearing capacity; inner friction; sleeve height; soil plug; tip thickness

## 1. Introduction

Pipe piles can either be open-ended or closed-ended. Previous studies have shown that the behaviour of open-ended piles is different from closed-ended piles (Szechy 1961, Randolph *et al.* 1979, Paikowsky and Whitman 1990). Open-ended driven piles are widely used as deep foundations, particularly in offshore constructions. Generally, it is accepted that a short open-ended pile produces a smaller bearing capacity than a similar closed-ended pile (Nauroy and Tirant 1983). However, a long open-ended pile such as the piles used in offshore constructions, can

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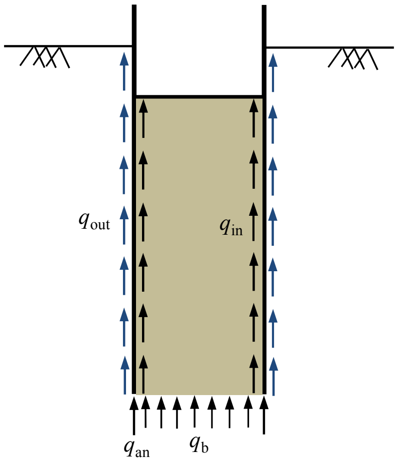



Fig. 1 The components of ultimate bearing capacity of an open-ended pile

produce a bearing capacity similar to a closed-ended pile due to the larger inner frictional resistance mobilised between the inner pile shaft and inner soil (Lehane and Randolph 2002). As given in Eqs. (1a) and (1b) (see Fig. 1 also), ultimate bearing capacity of an open-ended pile consists of three components such as annulus resistance, outer and inner frictional resistances.

$$q_u = q_{an} + q_{out} + q_{plug} \tag{1a}$$

Where $q_u$ is ultimate bearing capacity, $q_{an}$ is annulus resistance, $q_{out}$ is outer frictional resistance and $q_{plug}$ is plug resistance.

$$q_{plug} = \text{Min}\,(q_{in}, q_b) \tag{1b}$$

Where $q_{in}$ is inner frictional resistance and $q_b$ is base resistance.

When an open-ended pile is driven into a soil, underneath soil (i.e., the soils below the pile tip) penetrates into the pile and generate a soil column. This soil column is called a soil plug. As penetration continues, inner frictional resistance may develop and prevent further soil intrusion. An open-ended pile can have a bearing capacity similar to a closed-ended pile depending on the loading capacity of the soil plug. Therefore, knowledge of the formation of soil plug is imperative to understand the bearing capacity of open-ended piles.

If an open-ended pile, particularly a small diameter or long penetration pile, is driven under fully-plugged mode, it behaves similar to a closed-ended pile where the summation of $q_{an}$ and $q_{plug}$ of the open-ended pile (see Eq. (1a)) is equal to the base resistance of the closed-ended pile. In contrast, for an open-ended pile driven under fully coring (or unplugged) mode, its bearing capacity is the summation of $q_{an}$ and $q_{out}$ (Eq. (1a)) and this can be much smaller than that of a similar closed-ended pile depending on its wall thickness. However, most piles are driven under partially-plugged mode in practice (Tomlison 2004, Kikuchi 2011). Fig. 2 shows the modes of penetration of an open-ended pile related.

Many factors of pile installation and ground conditions can affect the formation of soil plug length (Paik and Salgado 2004). Although static penetration methods can lead to a formation of soil plug length, dynamic nature pile installation methods may not form a soil plug length

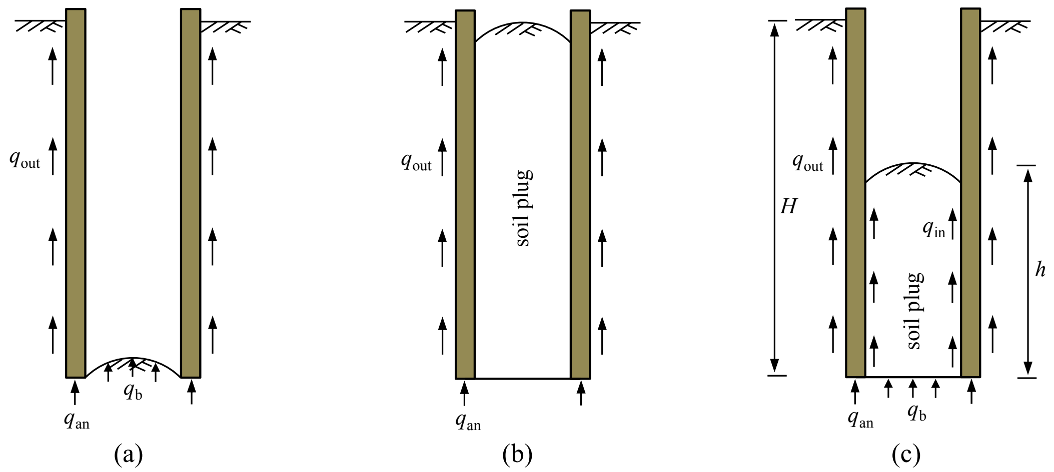



Fig. 2 The modes of penetration of an open-ended pile: (a) fully-plugged; (b) fully coring; and (c) partially-plugged mode

(Paikowsky *et al*. 1989, Paik and Lee 1993). It is also understood that loose ground conditions lead to higher degree of soil plugging (Paik and Salgado 2002, Paik *et al*. 2003). The uncertainty of the knowledge of soil plug length has led the design methods adopting different design parameters for open-ended piles. In Japan, most of the pile foundations are designed based on the JRA specifications for highway bridges (JRA 2002). In the JRA specifications, the ratio of embedment length (into the bearing stratum) to pile outer diameter is considered 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 the ICP method is that it considers only 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 ICP method may underestimate the bearing capacity of open-ended piles. HKU method, which was recently developed by Yu and Yang (2010) links the plug length ratio with the plug resistance. Reviews of widely used current design methods can be found in Lehane *et al*. (2005) and Schneider at al. (2008). The API specification also includes four CPT-based design methods for open-ended piles (API 2006). As reported in many design methods, it can be seen that the evaluation of inner frictional resistance has not been universally established due to the uncertainty of formation of soil plug length. The level of uncertainty associated with empirical correlations can be reduced through testing and site investigations (Zhang *et al*. 2004).

As discussed above, the accuracy of the estimation of bearing capacity of an open-ended pile depends heavily on the accuracy of inner frictional resistance. While the effects of ground conditions on soil plug formation have sufficiently been investigated (Hettler 1982, Paik and Salgado 2002, Paik *et al*. 2003), effects of pile geometry such as wall thickness at the pile base, inner diameter or sleeve length of a thickened wall at the pile tip on the formation of soil plug have scarcely been studied. In this research, the behaviour of open-ended piles of various tip thicknesses and sleeve lengths of a thickened wall at the pile tip was studied using model test piles. In the paper, the effects of these parameters (i.e., tip thickness and sleeve height) on inner frictional resistance and bearing capacity of the piles are explored. In addition, testing on model piles was conducted to study the effective soil plug length as the total soil plug length may not contribute to inner frictional resistance (Lehane and Gavin 2001, Kikuchi 2011).

## 2. Model ground and pile penetration method

The model ground was prepared in a soil tank with the dimension of 300mm inner diameter and 250 mm height as shown in Figs. 3(a) and (b). The soil tank has a top cover, which is fitted with a bearing house. The bearing house was designed to maintain the verticality of the driven piles during pile installation. The bearing house was designed to accommodate five piles (which can also be used to study effects of preceding piles on the bearing capacity of succeeding piles) as shown in Fig. 3(b). In this study, the central pile (see Fig. 3(b)) was used for the tests. Silica sand #5 was used to prepare the model ground. The physical properties and particle size distribution of

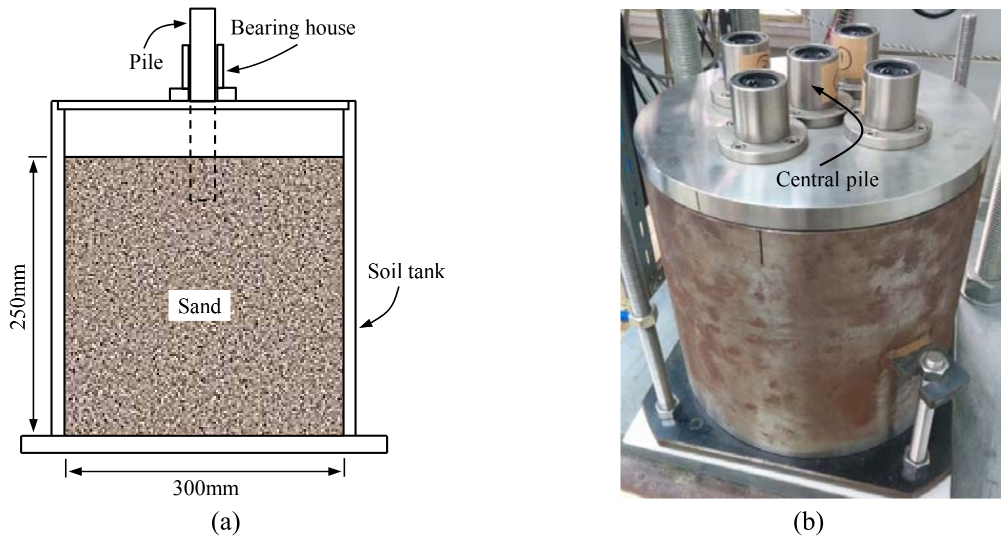



Fig. 3 (a) Schematic diagram (not to scale, only middle pile of the bearing house is included); and (b) photograph (with the full bearing house) of soil tank

Table 1 Physical properties of silica sand

| 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 |

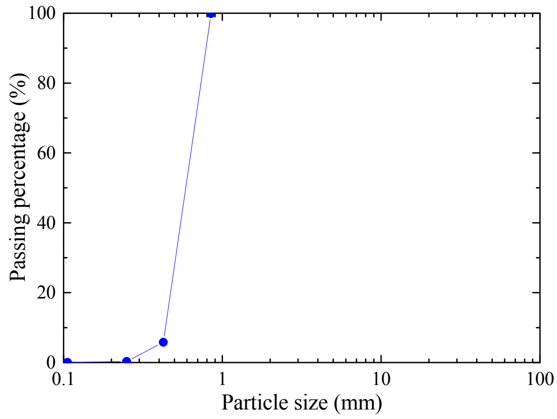



Fig. 4 Particle size distribution of silica sand

silica sand are given in Table 1 and Fig. 4 respectively. The model ground was prepared with 60-65% of relative density. The sand was poured from a tube of 30 mm diameter from a constant height to produce the required relative density (i.e., air pluviation method). A similar procedure of ground preparation has been used in Kikuchi (2011).

The loading apparatus is shown in Fig. 5. Static penetration with a penetration rate of 3mm/min was applied during the pile penetrations. The penetration resistance and penetration depth were measured using a load cell and external displacement transducer respectively during pile penetration as shown in Fig. 5. Since the penetration resistance was measured above the bearing house, the friction between a pile and the bearing house is also included in the measurement of the penetration resistance. However, it is assumed that the frictional force between a pile and the bearing house is small (as the piles under self-weights (e.g., 2.0 N for t-3.0 pile) penetrated through the bearing house) and consistent among all the piles. The piles were penetrated to the maximum possible depth of 130-140 mm.

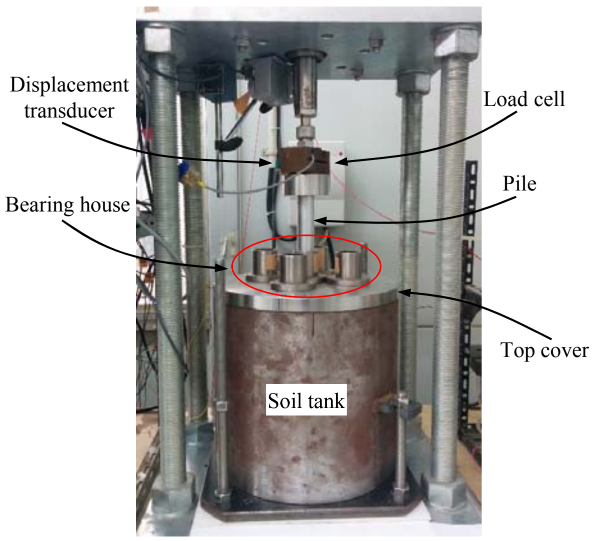


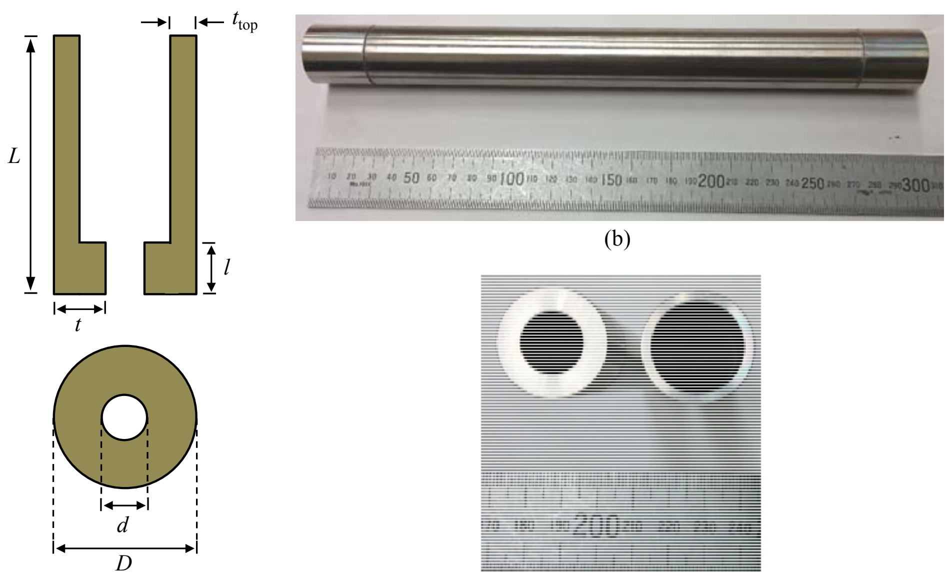

Fig. 5 Photograph of the loading apparatus

Table 2 The details of the model piles

| Pile notation | Tip thickness, $t$ (mm) | Sleeve Height, $l$ (mm) | Top thickness, $t_{top}$ (mm) | Length, $L$ (mm) | Outer diameter, $D$ (mm) | Inner diameter, $d$ (mm) | $l/D$ ratio | $D/t$ ratio | $A_{an}$ (mm$^2$)* | $A_{an}/A_t$ ratio* |
|---|---|---|---|---|---|---|---|---|---|---|
| t-3.0 | 3.0 | N/A | 3.0 | 300 | 30 | 24.0 | N/A | 10.0 | 254 | 0.36 |
| t-4.5 | 4.5 | | 4.5 | | | 21.0 | | 6.7 | 360 | 0.51 |
| t-6.5 | 6.5 | | 6.5 | | | 17.0 | | 4.6 | 480 | 0.68 |
| l-10 | 6.6 | 10 | 3.0 | | | 16.8 | 0.33 | 4.5 | 485 | 0.69 |
| l-30 | | 30 | | | | | 1.00 | | | |
| l-60 | | 60 | | | | | 2.00 | | | |

* $A_{an}$ is annular area and $A_t$ is total area covered by outer pile diameter

Stainless steel open-ended piles were used in the experimental work and six different open-ended piles were used for the tests. The details of the model piles are given in Table 2 and Fig. 6(a). Figs. 6(b) and (c) show photographs of a model pile. The piles of 3.0, 4.5 and 6.5 mm tip thickness (i.e., the wall thickness at the pile tip), which are indicated as t-3.0, t-4.5 and t-6.5 piles respectively (see Table 2), were used to study the effects of tip thickness on bearing capacity, particularly on formation of soil plug height. The piles of 10, 30 and 60 mm of sleeve length (i.e., height of the thickened wall at the pile tip), which are indicated as l-10, l-30 and l-60 piles respectively, were used to study the effects of sleeve length on bearing capacity, particularly on formation of soil plug height. Since the piles have a smaller ratio of outer diameter to thickness (i.e., $D/t$ ratio) than the piles used in practice (Gudavalli *et al*. 2013), the laboratory model tests




(a) (b) (c)

Fig. 6 (a) Schematic diagram (not to scale); (b) photograph of longitudinal view; and (c) the two ends of a model pile ($l$ is sleeve length and $t$ is wall thickness at the pile base)

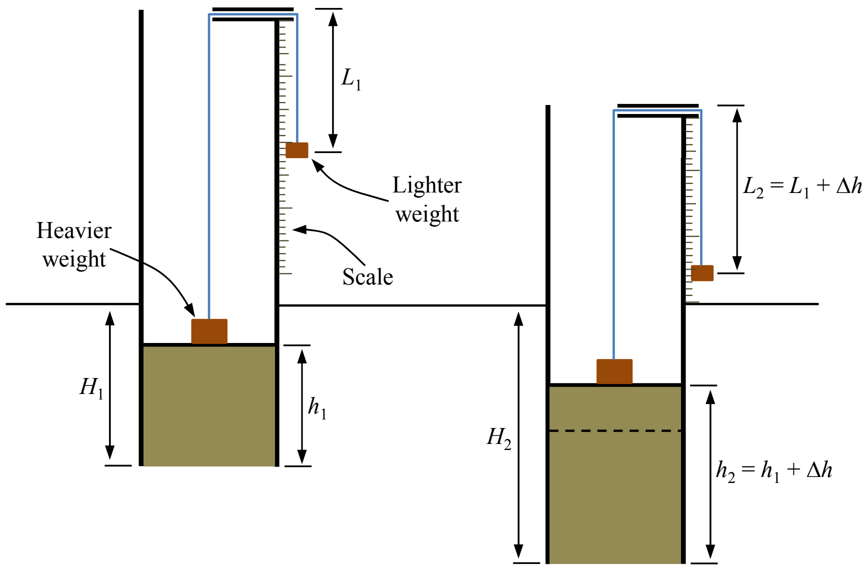



Fig. 7 The measurement method of the soil plug height (*h* is soil plug height and *H* is penetration depth)

might have some scale effects, particularly when *D*/*t* ratio is quite small. However, as the main purpose of this paper is to compare test results from piles of different geometrical conditions and the absolute value of bearing capacity of each pile is not a consideration in this study, scale effects were not considered in this paper. We have planned an experimental program that uses large diameter piles in the next step of the research, from which we expect to thoroughly study the scale effect.

In some of the tests, soil plug length was also measured using a scale marked on the pile as shown in Fig. 7. In this method, two different weights were connected by a string and the smaller weight rested on the soil plug. Pile penetration was stopped at 10mm measurement interval to measure the soil plug length. There can be some errors on the measured heights due to irregularities of the top surface of inner soils. However, we assume that this is consistent among all the tests, hence the results on inner soil height can be accepted. In two tests (i.e., Test-t-4.5-spr,1D and Test-l-60-spr,1D; see Table 3), the formed soil plugs were removed after the penetration depth of 1*D* length (*D* is pile outer diameter) using a hand vacuum cleaner after stopping the penetration. A small camera (with an in-built special lengthy cable) was also inserted into the pile to ensure that the additional soil underneath the pile tip is not removed by the vacuum cleaner. Table 3 gives the details of the tests.

## 3. Results and discussion

Two indexes widely used to discuss the inner frictional resistance of an open-ended pile (i.e., plug length ratio, *PLR* and incremental filling ratio, *IFR*) are introduced in here (Paikowsky *et al.* 1989, Paik and Lee 1993). The definition of *PLR* is given in Eq. (2) (see Fig. 8 also). The *PLR* gives an average behaviour of plugging state for a long penetration depth. The *IFR* defined in Eq. (3) (see Fig. 8 also) gives the instantaneous plugging state at small penetration depth. As plugging

Table 3 The details of the tests

| Test notation | Pile notation | Penetration method* | Measurements† |
|---|---|---|---|
| Test t-3.0 | t-3.0 | Monotonic penetration | *P* and *H* |
| Test t-4.5 | t-4.5 | | |
| Test t-6.5 | t-6.5 | | |
| Test t-3.0-h | t-3.0 | Monotonic penetration with unloading at a 10 mm interval l-60 | *P*, *H* and *h* |
| Test t-6.5-h | t-6.5 | | |
| Test l-10-h | l-10 | | |
| Test l-30-h | l-30 | | |
| Test l-60-h | l-60 | | |
| Test t-4.5-u,lD | t-4.5 | Monotonic penetration with unloading at 1*D* depth | *P* and *H* |
| Test t-4.5-spr,1D | t-4.5 | Monotonic penetration with the soil plug removed at 1*D* depth | |
| Test l-60-u,lD | l-60 | Monotonic penetration with unloading at 1*D* depth | |
| Test l-60-spr,1D | l-60 | Monotonic penetration with the soil plug removed at 1*D* depth | |

* *D* is outer pile diameter, †*P* is penetration resistance, *H* is penetration depth and *h* is soil plugheight

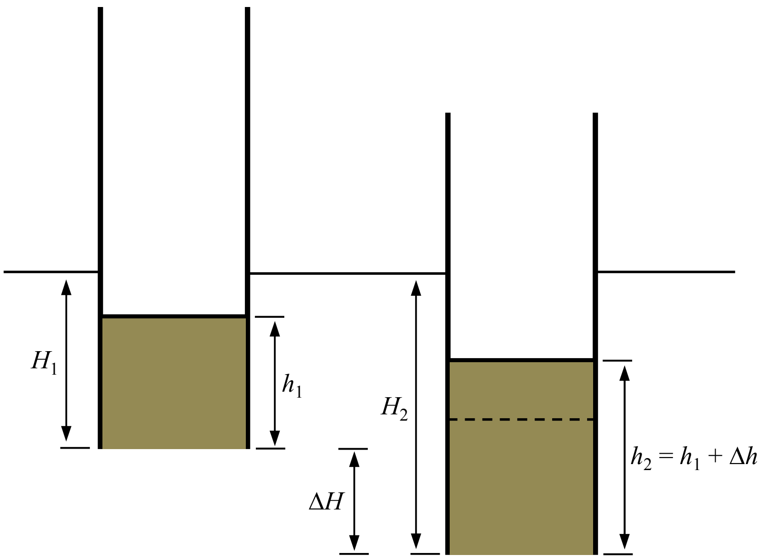



Fig. 8 The definitions of the parameters used in the evaluation of the plug length ratio and incremental filling ratio (*h* is soil plug height and *H* is penetration depth)

condition can vary with pile penetration, the *IFR* gives a better indication of plugging condition than *PLR*.

$$PLR = \frac{h}{H} \quad (2)$$

Where *PLR* is plug length ratio, *h* is soil plug height and *H* is penetration depth.

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

Where *IFR* is incremental filling ratio, $\Delta h$ is the change of soil plug height for a penetration depth of $\Delta H$.

### 3.1 Effects of wall thickness at the pile tip

Fig. 9 shows the results of penetration resistance versus penetration depth for the piles with different wall thicknesses at the pile tip (i.e., $t$ = 3.0, 4.5 and 6.5 mm). As shown in Fig. 9, the pile of 3.0 mm wall thickness gives the smallest penetration resistance, which can be attributed to the smallest annular area (see Table 2), followed by the pile of 4.5 mm wall thickness. As expected, a pile of a larger wall thickness produces a higher penetration resistance. Fig. 10 shows the variation of soil plug height versus penetration depth of the piles of 3.0 and 6.5 mm wall thickness (i.e., see Test t-3.0-h and Test t-6.5-h of Table 3). As Fig. 10 shows, soil plug height increases in thicker walled pile (i.e., smaller inner pile diameter) with a smaller incremental rate than thinner walled pile (i.e., larger inner pile diameter). However, a thinner walled pile tends towards a constant soil plug height after some penetration depth. Therefore, at deep penetration depths, a thicker walled pile produces a higher soil plug height. Figs. 11(a) and (b) show the relationships of plug length ratio (*PLR*) and incremental filling ratio (*IFR*) versus penetration depth of the piles of 3.0 and 6.5 mm wall thickness (i.e., t-3.0 and t-6.5 piles) respectively. The results of the *PLR* suggested that the thinner walled pile (i.e., with larger inner pile diameter) produces larger values of *PLR* at shallow penetration depths while the behaviour can be the opposite at greater penetration depths (e.g., below 140 mm) if the same trend continues. Gudavalli *et al.* (2013) also suggested that for large diameter piles used in practice (e.g. 406 – 914 mm diameters) driven into dense to very dense sandy soils by 10 – 30 m depth, the *PLR* increases with pile diameter. The results of *IFR*, which gives a better indication of the plugging condition, suggest that thinner walled piles produce a higher degree of soil plugging (i.e., smaller values of *IFR*) at greater penetration depths. However,

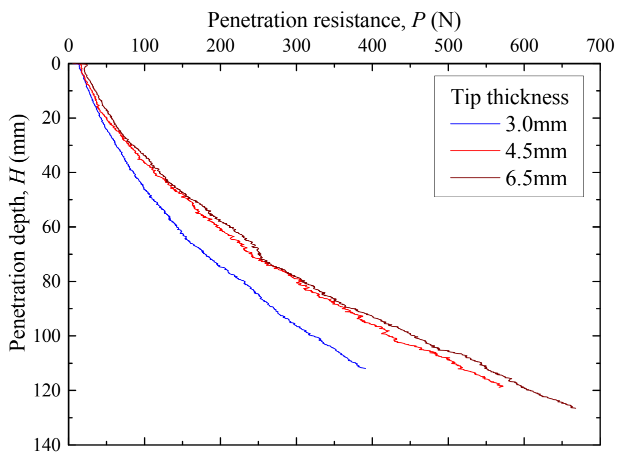



Fig. 9 Effects of tip thickness on bearing capacity

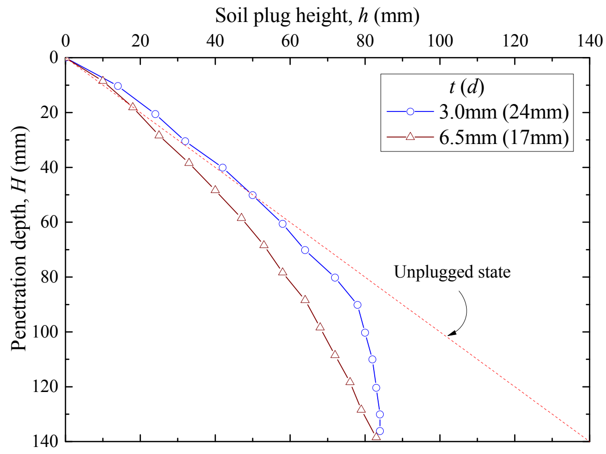



Fig. 10 Effects of tip thickness on soil plug height (*t* is tip thickness and *d* is inner pile diameter)

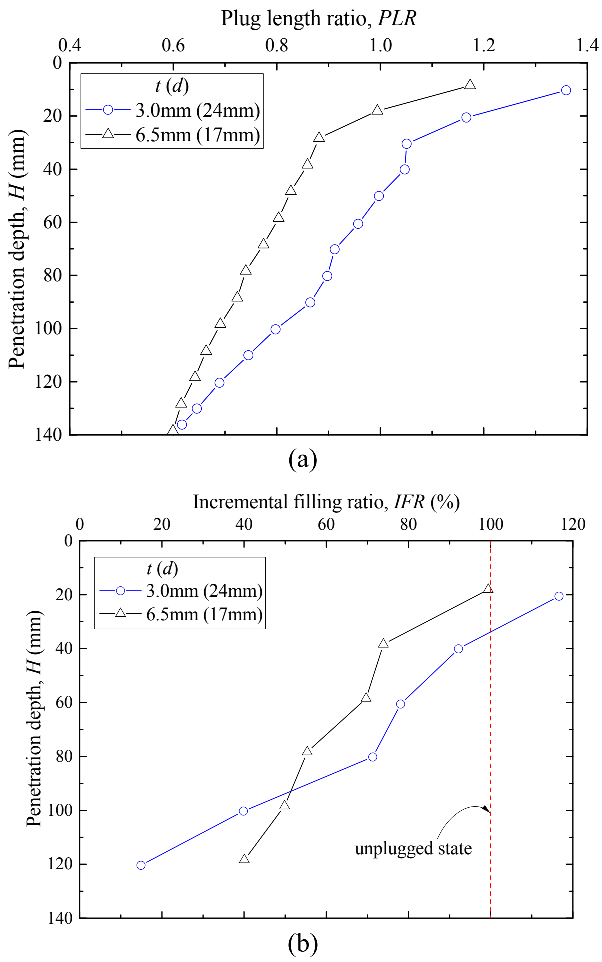



Fig. 11 Effects of tip thickness on (a) plug length ratio; and (b) incremental filling ratio (*t* is tip thickness and *d* is inner pile diameter)

we recommend to conduct more tests using the piles of different thickness to derive concrete conclusions as the results in this paper were obtained from only two model piles.

### 3.2 Effects of sleeve length

Fig. 12 shows the results of penetration resistance versus penetration depth of the piles of different sleeve lengths (i.e., $l$ = 10, 30, 60 and 300 mm). As shown in Fig. 12, the pile of 10 mm sleeve length gives the smallest penetration resistance, followed by the piles of 30, 60 and 300 mm sleeve length (note: the pile of 6.5 mm tip thickness does not have a thickened wall at the pile tip. Therefore, the entire length of 300 mm is considered as the sleeve length for a comparison in here). The results also indicate that the penetration resistance is independent of the sleeve length of over 30 mm (which is equal to a 1$D$ length) since all the piles of 30, 60 and 300 mm sleeve length produced a similar penetration resistance. The annulus resistance should be same for all the piles as annular area is almost the same (see Table 2). Outer frictional resistance, $q_{out}$ (see Eq. (4)) was found to be 2 2N (assuming 35 degree of soil frictional angle, $\phi$; 0.7$\phi$ of frictional angle between the pile shaft and soil, $\delta$; 0.675 of coefficient of lateral earth pressure, $k$ according to Tomlinson (2004)). As $q_{out}$ is small due to a lack of overburden pressure and equal for all the piles, the difference in penetration resistance between the piles of 10 and 30 mm sleeve length can be attributed to the inner frictional resistance. Inner frictional resistance of the piles of 30, 60 and 300 mm sleeve length seems to be equal. Therefore, it can be interpreted as 30 mm (or equal to 1$D$ length) sleeve length mobilises the inner frictional resistance. Thus, the results suggest that the pile of 30 mm sleeve length is the best pile among all the piles considering economic reasons.

$$q_{out} = Aq \tag{4}$$

Where $q_{out}$ is outer frictional resistance, $A$ is effective surface area of pile shaft and $q$ is unit outer frictional capacity given in Eq. (5).

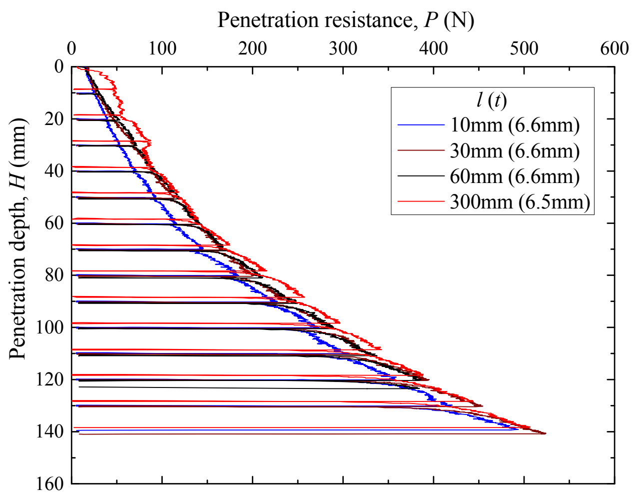



Fig. 12 Effects of sleeve length on bearing capacity ($l$ is sleeve length and $t$ is wall thickness at the pile base)

$$q = k\sigma \tan\delta \tag{5}$$

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

Fig. 13 shows the variation of soil plug height versus penetration depth of the piles of 10, 30, 60 and 300 mm sleeve length. As Fig. 13 shows, the piles of 60 and 300 mm sleeve length produce the highest soil plug height and nearly similar to that of a fully coring (or unplugged) mode compared to the piles of 10 and 30 mm sleeve length (i.e., which produced similar soil plug heights). Figs. 14(a) and (b) show the variations of plug length ratio and incremental filling ratio respectively versus penetration depth of the piles of 10, 30, 60 and 300 mm sleeve length. As expected from the results of soil plug height, the results of the plug length ratio, *PLR* indicates that the piles of 60 and 300 mm sleeve length have higher values of the *PLR* than those of the piles of 10 and 30 mm sleeve height. The results of incremental filling ratio, *IFR* suggest that, although all the piles reach around 30-40% of *IFR* at approximately 120mm penetration depth (i.e., 4*D* depth), the piles of a shorter sleeve length (e.g., 10 and 30 mm) achieve 30-40% of the *IFR* at penetration depths as shallow as 40 – 60 mm (i.e., < 2*D* depth). This indicates that the piles penetrated into shallow depths need a shorter sleeve length to produce a sufficient inner frictional resistance. However, it can be seen that the piles of 10 and 30 mm sleeve length (i.e., equal to ≤ 1*D* length) remain at 30-40% of the *IFR* (i.e., partially-plugged condition) even at greater penetration depths while the piles of more 60 mm sleeve length (i.e., equal to 2*D* length) may develop a fully-plugged condition at greater penetration depths.

The *IFR* results suggest that the *IFR* should be determined at a sufficiently large measurement interval (of penetration depth) since a small interval produces large fluctuations as seen in Fig. 15 (for the pile of 60 mm sleeve length). The soil plug height was measured at a 10 mm interval during the testing. However, large fluctuations in the *IFR* evaluated at 10 mm measurement interval led to use a 20 mm measurement interval to evaluate the *IFR*. Therefore, it is recommended to use a measurement interval slightly larger than a 1*d* (we used 1.2*d*; *d* is inner pile diameter) to evaluate the *IFR*. We used the inner diameter over outer pile diameter since the

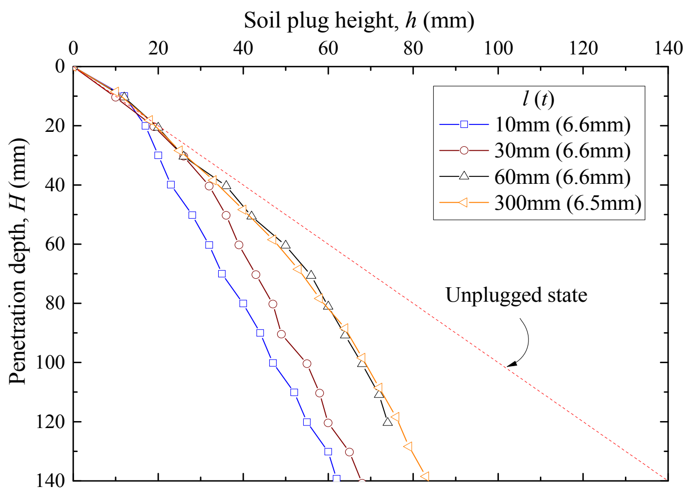
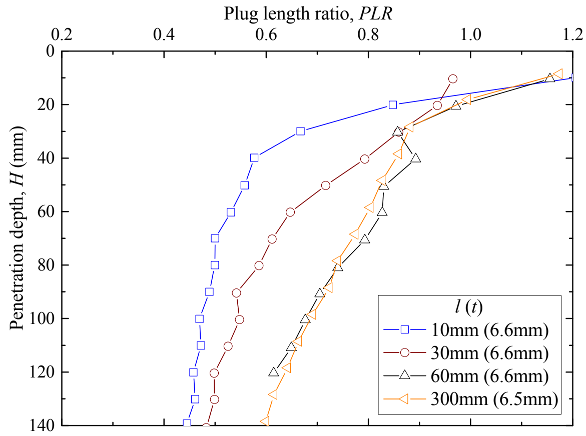
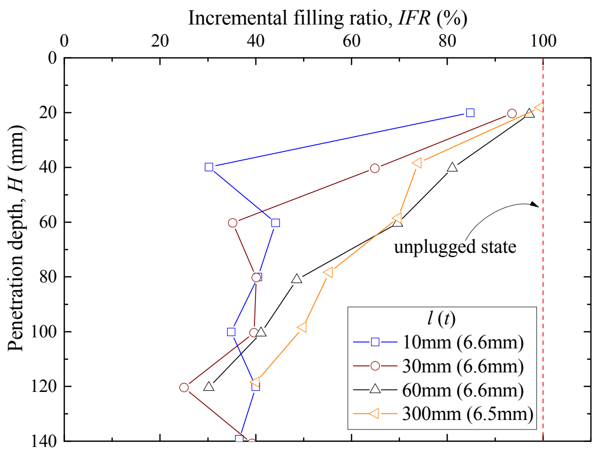



Fig. 13 Effects of sleeve length on soil plug height (*l* is sleeve length and *t* is wall thickness at the pile base)




(a)




(b)

Fig. 14 Effects of sleeve length on (a) plug length ratio; and (b) incremental filling ratio (*l* is sleeve length and *t* is wall thickness at the pile base)

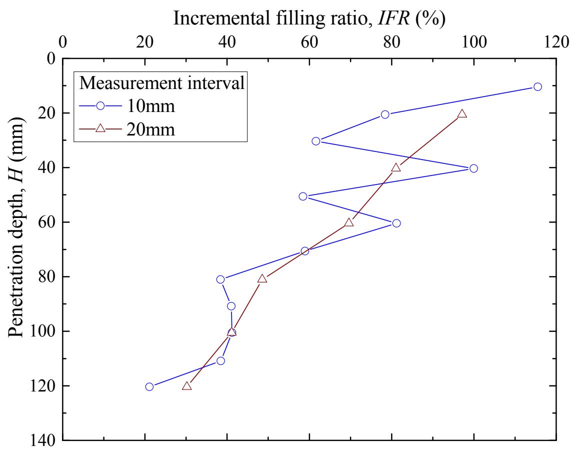



Fig. 15 Effects of the measurement interval on evaluation of incremental filling ratio

soil plug height can be correlated with the inner pile diameter better. However, more model tests would be required to clearly understand the influence of inner and outer pile diameters on the evaluation of the *IFR*. Paik and Salgado (2002) has also used about 1.1*d* measurement interval to determine the *IFR*. The use of a larger measurement interval can result in similar values of the *PLR* and *IFR* (if the *IFR* is given in decimal).

It should be noted that since inner diameter varies along the pile length (when the sleeved piles are used), the effects of varying inner diameter on soil plug height should be discussed based on the change in soil volume and density with the penetration depth. In the literature, most of the studies used straight piles (i.e., the piles without a sleeve at the pile tip). Hence, no issues have been observed related to the soil plug height measurements (e.g., Randolph *et al*. 1992, Miller and Lutenegger 1997, Paik *et al*. 2003). When the penetration depth becomes larger than the sleeve length of a pile of a thickened wall at the pile tip, soil plug height might have some variations owing to the variations in inner soil volume and density with pile penetration. The conclusions in this paper were based on limited experiments and a detailed study is recommended in order to draw concrete conclusions on soil plug height measurements.

### 3.3 Effective soil plug length

The formed soil plug was removed at penetration depth equal to 1*D* (*D* is pile outer diameter) in two tests (i.e., Test t-4.5-spr,1D and Test l-60-spr,1D of Table 3) to understand the effective soil plug length. It has been previously reported that the shear resistance of soil plug is concentrated at the pile tip (De Nicola and Randolph 1997, Lehane and Gavin 2001). Therefore, the purpose of this paper is to study the penetration depth required to recover the penetration resistance developed before the soil plus is removed. Figs. 16(a) and (b) show the results of the piles of 4.5 and 6.6 mm wall thickness (i.e., pile notations of t-4.5 and l-60 respectively; Table 2). As Figs. 16(a) and (b) show, the penetration resistance recovered at 15-20 mm penetration depth after the resumption of penetration. If we assume that a sufficient plug has been formed at 30mm penetration depth (hence, a reasonable inner frictional resistance), it is clear that the difference in penetration resistance between the two tests (i.e., 1*D* unloading (i.e., unloading at 1*D* depth) and 1*D* soil plug removal cases) after the penetration resumed can be attributed to inner frictional resistance. The results of the experiments indicate that the effective soil plug length is around 15-20 mm (i.e., about 1*d*; *d* is inner pile diameter) from the pile tip.

## 4. Conclusions

Laboratory model tests were conducted using open-ended piles of different wall thicknesses and sleeve length of a thickened wall at the pile base. The effects of the geometrical properties of the open-ended piles on bearing capacity, particularly inner frictional resistance were discussed using the results of soil plug height. The following conclusions were drawn from the model test results.

- Bearing capacity increases with tip thickness, which is attributed to the increase of annulus area.
- Soil plug height is dependent on wall thickness at the pile base. The penetration of thinner walled piles is closer to unplugged state than thicker walled piles at shallow penetration depths although it is the opposite at deep penetration depths.

- The results of incremental filling ratio revealed that the piles of smaller wall thickness produce higher degree of soil plugging (thus, larger inner frictional resistance) at greater penetration depths.
- Bearing capacity of the piles of a smaller sleeve length (e.g., ≤ 1*D* length; *D* is pile outer diameter) is dependent on sleeve length while it is independent on the sleeve length for the piles of a sleeve length larger than 1*D* length. Therefore, we conclude that inner frictional resistance is mobilised within 1*D* length from the pile tip.
- Soil plug height is dependent of sleeve length of up to 2*D* length and independent beyond a 2*D* length. The piles of a smaller sleeve length (e.g., ≤ 1*D* length) produce higher degree of soil plugging at shallow penetration depths, in contrast to the piles of a larger sleeve length (i.e., ≥ 2*D* length) that produce higher degree of soil plugging at greater penetration depths. We also observed there are no effects from the sleeve length of more than 2*D* length on the degree of soil plugging.
- The results also revealed that the effective soil plug length is around 1*d* (*d* is pile inner diameter) from the pile tip.
- We also recommended that the incremental filling ratio should be evaluated at around a 1*d* measurement interval to reduce fluctuations of it along the penetration depth.

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