Journal of GeoEngineering, Vol. 10, No. 3, pp. 75-82, December 2015
http://dx.doi.org/10.6310/jog.2015.10(3).1

EFFECTIVE LENGTH OF THE SOIL PLUG OF INNER-SLEEVED OPEN-ENDED PILES IN SAND

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ABSTRACT

The bearing capacity of open-ended piles depends largely on the inner frictional contribution. The degree of the soil plugging determines the inner frictional resistance. While many factors influence the degree of soil plugging, this paper discusses the effects of inner sleeve heights on the inner frictional resistance. In this paper, the effective length of the soil plug was also studied using small-diameter sleeved piles penetrated into a medium-dense sandy ground. At first, the effects of the sleeve heights on the bearing capacity, in particular inner frictional resistance were discussed using a simple analysis method. The results suggest that a higher sleeve height increases the bearing capacity due to the increase in inner frictional resistance. A series of experiments conducted by removing the generated soil plug reveal that, not only the sleeve height affects the penetration resistance, but also the effective soil plug length is roughly two times the pile outer diameter. The experiments also indicate that the penetration resistance of the soil plug removed piles do not recover to the non-soil plug removed pile when the sleeve height is quite small. The results of the soil plug heights suggest that it is influenced by the sleeve height. The results of incremental filling ratio and plug length ratio were also discussed. The incremental filling ratio and plug length ratio of the sleeved-piles were evaluated using a new simple method to ensure that the originally defined equations for the non-sleeved piles are compatible with the sleeved piles. The results of the corrected incremental filling ratio and plug length ratio give a better indication on the soil plugging, particularly at the early penetration depth.

Key words: Bearing capacity, effective length, inner friction, inner sleeve, open-ended pile, soil plugging.

1. INTRODUCTION

In recent times, open-ended driven piles have gained popularity, particularly in offshore deep foundations due to smaller driving resistance compared to closed-ended piles. The constructions of large infrastructure projects such as sea ports and airports have demanded long and large diameter open-ended piles. Previous studies have shown that the behaviour of open-ended piles is different from closed-ended piles (Randolph *et al.* 1979; Paikowsky and Whitman 1990; Leland 1991; Lee *et al.* 2003; Paik *et al.* 2003; Xu *et al.* 2008). It is understood that a short open-ended pile produces a smaller bearing capacity than a similar closed-ended pile. However, a long open-ended pile can produce a bearing capacity similar to a closed-ended pile due to large inner frictional resistance mobilised 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) (see Fig. 1 also). 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.

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

where Q_u is bearing capacity, Q_{an} is annulus resistance, Q_{out} is outer frictional resistance and Q_{plug} is plug resistance (see Eq. (2)).

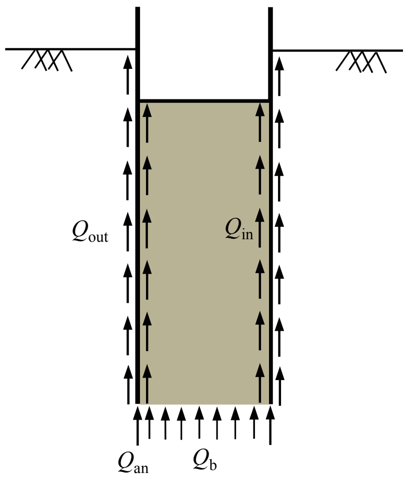

Fig. 1 The components of the bearing capacity of an open-ended pile

$$Q_{plug} = \min(Q_{in},\ Q_b) \quad (2)$$

where Q_{plug} is plug resistance, Q_{in} 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. As penetration continues, inner frictional resistance mobilised between the pile inner shaft and inner soil may develop and prevent further soil intrusion. Depending on the degree of soil plugging, an open-ended pile can produce a similar bearing capacity as a closed-ended pile. Figures 2(a) ~ 2(d) show the modes of penetration of

Manuscript received May 14, 2015; revised September 9, 2015; accepted September 16, 2015.
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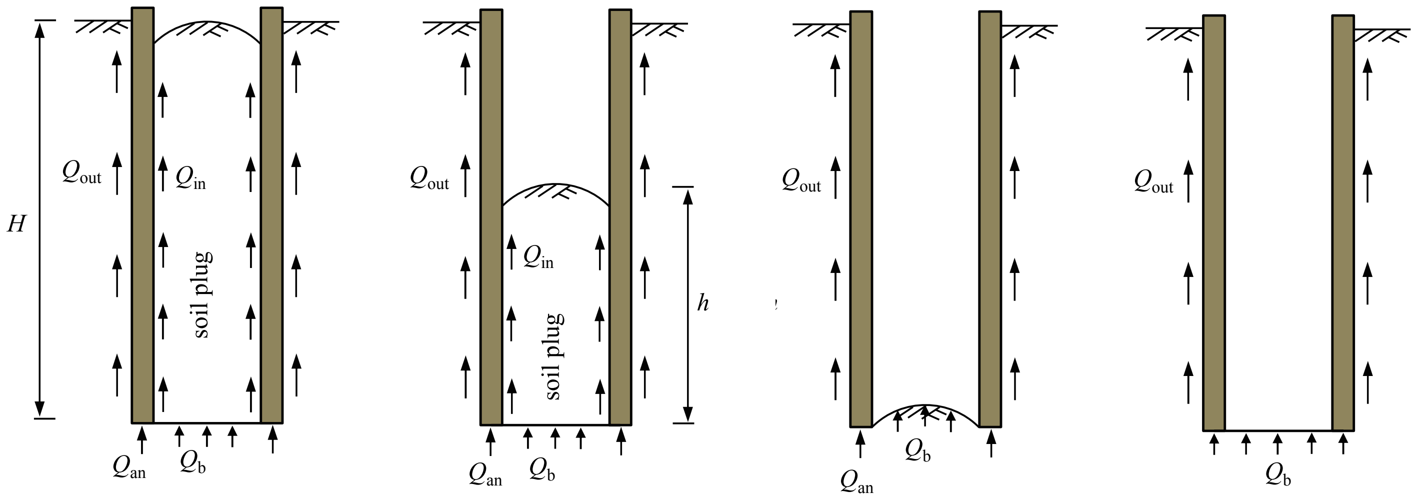


(a) Fully coring mode for an open-ended pile
(b) Partially-plugged mode for an open-ended pile
(c) Fully-plugged mode for an open-ended pile
(d) A closed-ended pile

Fig. 2 The modes of penetrations

open- and closed-ended piles. A fully-plugged open-ended pile (see Fig. 2(c)) behaves similar to a closed-ended pile (see Fig. 2(d)). However, most piles in practice are driven under partially-plugged mode (Tomlinson 2004; Kikuchi 2010). Due to a lack of inner frictional resistance, an unplugged (or fully coring) open-ended pile produces a smaller bearing capacity than its fully-plugged or partially-plugged counterparts. Although a large soil plug is developed in an unplugged open-ended pile (see Fig. 2(a)), it produces 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 (or loading).

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) compared the effects of installation methods on the degree of soil plugging using static and dynamic pile installation methods. They concluded that dynamic installation methods such as impact and vibratory pile driving do not encourage soil plugging compared to the static methods. The effects of ground conditions on the soil plug formation have been investigated by Hettler (1982), Paik and Salgado (2002) and Paik *et al*. (2003) among many others. They reported that loose ground conditions lead to higher degree of plugging conditions (Paik and Salgado 2002; Paik *et al*. 2003). The effects of pile diameter on the inner frictional resistance have also been studied by a few researchers including Gudavalli *et al*. (2013) and Henke and Bienen (2013). Gudavalli *et al*. (2013) indicated that the small diameter piles produce higher degree of soil pugging than large diameter piles. The effects of lateral stress on shaft friction have been included in the design methods by Lehane *et al*. (2005) and Jardine *et al*. (2005). However, their proposed formulae were based on closed-ended piles where the shaft friction is limited to the outer pile shaft and outer soil. Recently, Henker and Bienen (2013) discussed the effects of lateral stress on inner frictional resistance, where they reported that there is a higher coefficient of lateral earth pressure on the inner pile shaft than the outer pile shaft.

While the effects of installation methods and ground conditions on the soil plugging have been studied in the past, the effects of the inner sleeves attached at the pile base of the open-ended piles on the mechanism of soil plugging have not been studied. In this research, the behaviour of open-ended piles attached with an inner sleeve was studied, particularly discussing the effective length of the soil plug by conducting a series of model experiments of soil plug removed cases.

2. METHODOLOGY

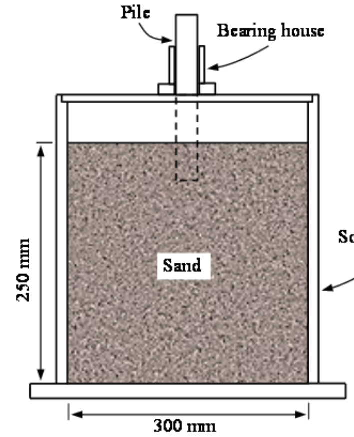
The model ground was prepared in a soil tank with the dimension of 300 mm inner diameter and 250 mm height as shown in Fig. 3(a). The soil tank is placed on a sliding plate such that it can be moved when it is required. The bearing house fitted on the top cover was designed to maintain the verticality of the piles during the pile installation and loading. The loading apparatus is shown in Fig. 3(b). 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. 4 respectively. The density tests were conducted according to JIS (2009). The minimum dry density was obtained by preparing the test sample with zero height. The maximum dry density was obtained by vibrating the prepared test sample for three minutes. Then, the extreme void ratios (*i.e.*, maximum and minimum values) were obtained as given in Eqs. (3) and (4) respectively.

$$e_{\max} = \frac{G_s \rho_w}{\rho_{d,\min}} - 1 \tag{3}$$

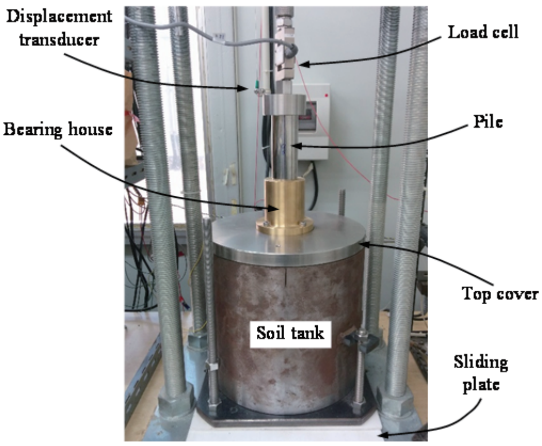
where $e_{\max}$ is maximum void ratio, G_s is specific gravity, ρ_w is water density and $\rho_{d,\min}$ is minimum dry density.

$$e_{\min} = \frac{G_s \rho_w}{\rho_{d,\max}} - 1 \tag{4}$$

where $e_{\min}$ is minimum void ratio, G_s is specific gravity, ρ_w is water density and $\rho_{d,\min}$ is maximum dry density.



(a)



(b)

Fig. 3 (a) A schematic diagram of the soil tank and (b) A photograph of the loading apparatus

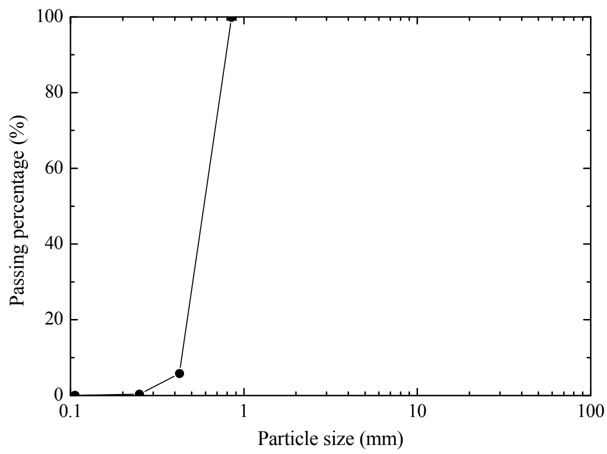


Fig. 4 Particle size distribution of silica sand

The model ground was prepared with 60% of relative density. The relative density, D_r was determined using Eq. (5). Before the model tests were conducted, the silica sand was poured to the soil tank through a tube of 30 mm diameter from different constant heights to find the relationship of relative density and the falling height of the sand using the air pluviation method. Then, the required relative density (*i.e.*, 60%) was achieved during the ground preparation for pile testing using the pre-determined falling height of the sand.

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, ρ_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

$$D_r = \frac{(e_{max} - e)}{(e_{max} - e_{min})} \times 100\,(\%) \quad (5)$$

where D_r is relative density, e_{max} is maximum void ratio, e is void ratio of the sample and e_{min} is minimum void ratio.

The static penetration with a penetration rate of 3 mm/min was applied during the pile penetration. It should be noted that, the loading rate is not an influencing factor here as dry sand was used for the model ground (Henke and Bienen 2013). The penetration resistance, P and penetration depth, H were measured during the loading. The penetration resistance was measured at the pile head (see Fig. 3(b)). Therefore, a small consistent friction between the pile and bearing house is included in the measurement. However, as the piles penetrated through the bearing house under its self-weight, the friction between the pile and bearing house should be very small (*i.e.*, less than 2 N as the pile of the smallest weight penetrated under its self-weight). The displacement of the piles was measured at the pile head using an external displacement transducer (see Fig. 3(b)). Soil plug height, h 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. 5. After the loading is stopped, the string is inserted into the pile and the soil plug height is measured using the scale.

The generated soil plug was removed in some experiments such that the effective height of the soil plug can be studied. The soil plugs were removed after 1.0D, 1.5D, 2.0D and 2.5D (D is pile outer diameter) penetration depths. The soil tank was moved slightly away from the loading rod using the thin sliding plate, on which the soil tank is placed (see Fig. 3(b)), just to have sufficient space to insert the cable of a vacuum cleaner. The vacuum cleaner should be less powerful such that it does not disturb the soil beneath the pile base. Also, during the removal of the soil plug, a small camera was also inserted into the pile using its small diameter cable to ensure that any soil beneath the pile base is not removed by the vacuum cleaner. The soil of the soil plug was removed step by step such that we can observe the height of the soil plug remained by inserting the scaled-mark string into the pile.

Stainless steel piles were used in the experimental work. Two open-ended and one closed-ended pile of different geometrical properties were used for the model tests as given in Table 2 and Fig. 6. In pile notations of P_{50}-4.0-10 (see Table 2), 50 is pile

Table 2 The details of the model piles

Pile notation	Pile Type†	Tip thickness, t (mm)	Sleeve height, l (mm)	Pile inner diameter, d (mm)	Pile length, L (mm)	Pile outer diameter, D (mm)	D/t ratio	Annular area, A_{an} (mm^2)	Area ratio*, A_{an} / A_t
P_{50}-4.0-10	OE	4.0	10	42	380	50	12.5	578.1	0.294
P_{50}-4.0-100	OE	4.0	100	42	380	50	12.5	578.1	0.294
P_{50}-0.0-380	CE	N/A	N/A	N/A	380	50	N/A	1963.5	1.000

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

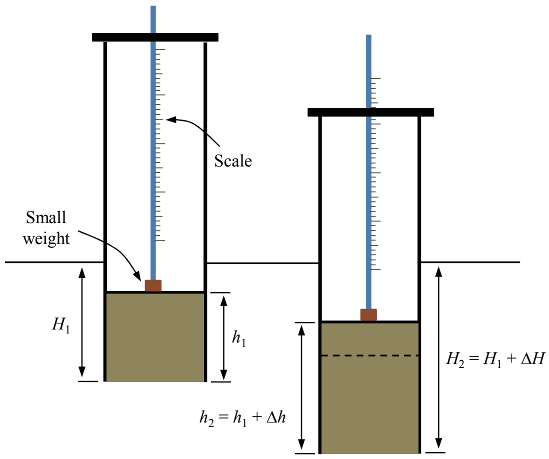


Fig. 5 The measurement of the soil plug height

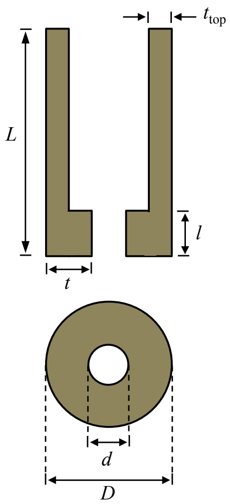


Fig. 6 Schematic diagram of an open-ended pile

outer diameter (in mm), 4.0 is wall thickness at the pile tip (in mm) and 10 is sleeve height (in mm). The open-ended piles have 2 mm of top thickness (t_{top}) above the inner sleeve. When the top wall thickness is considered as the wall thickness, the piles give a ratio of 25 for D/t_{top} which is within the range (*i.e.*, 15 ~ 45) reported by Jardine and Chow (2007) for typical offshore piles. However, when the inner sleeve is introduced to the piles (which gives 4 mm wall thickness at the pile base), the ratio reduced to 12.5, which is slightly below the range for typical offshore piles. However, given that our discussion in this paper is not on the absolute value of the bearing capacity, the piles should give acceptable results. Kikuchi (2010) has reported that the inner frictional resistance is mobilised within 2d distance (d is pile inner diameter) from the pile tip. Therefore, we selected the maximum value for the sleeve height, l as 100 mm, which is equal to 2.0D (D is pile outer diameter). Also, we have an open-ended pile with a small sleeve height (*i.e.*, 10 mm).

3. RESULTS

Figure 7 shows the results of penetration resistance versus penetration depth for the piles. It clearly indicates that the closed-ended pile (*i.e.*, P_{50}-0.0-380) produces a larger penetration resistance than same diameter open-ended piles. Theoretically, only a fully-plugged open-ended pile (*i.e.*, 0% of the incremental filling ratio) can produce a penetration resistance similar to a closed-ended pile. The results also indicate that the sleeve height influences the penetration resistance, where the pile with a higher sleeve height produces a larger penetration resistance. It should be noted that since the annular area is equal for the two open-ended piles (*i.e.*, P_{50}-4.0-10 and P_{50}-4.0-100), the annulus resistance can be assumed to be equal. Then, the difference in penetration resistance should be attributed to the difference in inner frictional resistance given that the outer frictional resistance should also be equal due to the same conditions of pile outer shafts and ground conditions.

3.1 Inner Frictional Resistance

The outer frictional resistance, Q_{out} can be evaluated from Eq. (6). We calculated Q_{out} to be small at 8.8 N at 150 mm depth (for a 35° of soil frictional angle, ϕ; 0.6ϕ of frictional angle between the pile shaft and soil, δ; 0.45 of coefficient of lateral earth pressure, K_h assumed according to Tomlinson (2004)). The annulus resistance, Q_{an} can be calculated using the area ratio (*i.e.*, A_{an} / A_t) given in Table 2 and total resistance, Q_t (Q_t is equal to the penetration resistance, P) of the same diameter closed-ended pile as given in Eq. (8). In Eq. (8), it is assumed that the base resistance of a closed-ended pile is uniformly distributed throughout the bottom surface area. The inner frictional resistance, Q_{in} then can be calculated by subtracting Q_{an} from Q_t.

$$Q_{out} = Aq \tag{6}$$

where Q_{out} is outer frictional resistance, A is effective surface area of pile shaft and q is unit outer frictional resistance as given in Eq. (7).

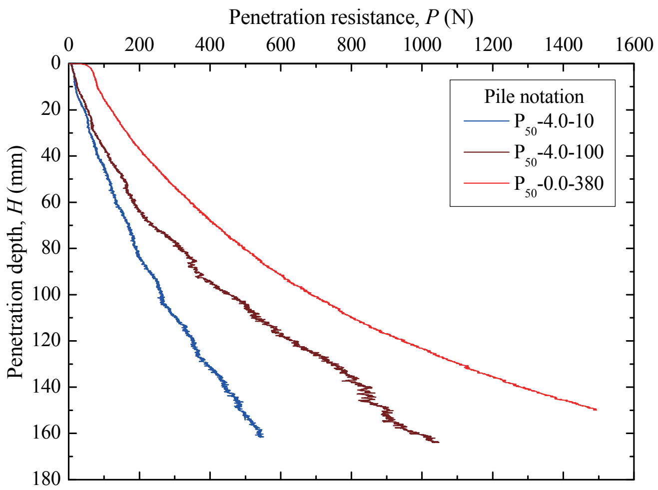


Fig. 7 Penetration resistance versus penetration depth

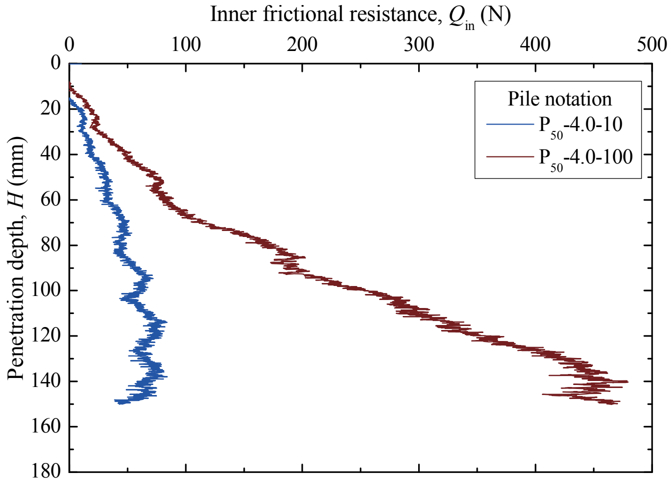


Fig. 8 Inner frictional resistance versus penetration depth

$$q = K_{\text{h}} \sigma \tan \delta \tag{7}$$

where q is unit outer frictional resistance, K_{h} is coefficient of lateral earth pressure, σ is effective overburden pressure and δ is frictional angle between the pile shaft and soil.

$$Q_{\text{an}} = \frac{A_{\text{an}}}{A_{\text{t}}} Q_{\text{t},D=50} \tag{8}$$

where Q_{an} is annulus resistance, A_{an} is annular area (see Eq. (9)), A_{t} is total area covered by outer diameter and $Q_{\text{t},D=50}$ is total resistance of 50 mm diameter closed-ended pile.

$$A_{\text{an}} = \frac{\pi}{4}(D^2 - d^2) \tag{9}$$

where A_{an} is annular area, D and d are pile outer and inner diameters respectively.

Figure 8 shows the inner frictional resistance versus penetration depth. It indicates that the inner frictional resistance is influenced by the sleeve height. The results indicate that a pile of a higher sleeve height produces a larger inner frictional resistance. It should also be noted that the inner frictional resistance may not increase with the sleeve height up to the total pile length as discussed by Kikuchi (2010), where it has been reported that the inner frictional resistance is limited to 2d distance (d is pile inner diameter) from the pile tip. This point will be discussed in a future study when more piles of different sleeve heights are tested.

3.2 Effective Length of the Soil Plug

Figures 9(a) and 9(b) show penetration resistance versus penetration depth for P_{50}-4.0-10 and P_{50}-4.0-100 piles respectively. In P_{50}-4.0-10 pile (see Fig. 9(a)), the penetration resistance of the soil plug removed piles do not recover to the non-soil plug removed pile even after 100 mm penetration depth (*i.e.*, more than 2.0D of penetration depth, where D is pile outer diameter). All the loading curves are roughly parallel in Fig. 9(a). Therefore, the penetration resistance of the soil plug removed piles do not recover to the non-soil plug removed pile within the penetration depth achieved here (*i.e.*, 40 ~ 100 mm). In contrast, Fig. 9(b) indicates that the penetration resistance of the soil plug removed

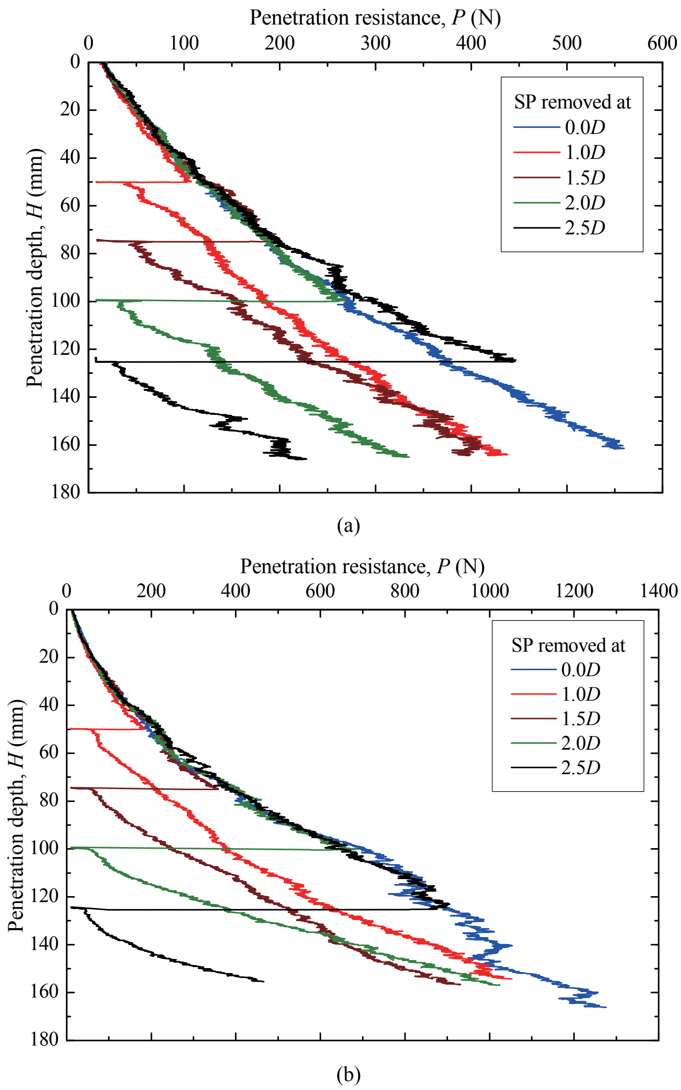


Fig. 9 Penetration resistance versus penetration depth of (a) P_{50}-4.0-10 and (b) P_{50}-4.0-100 pile (SP is soil plug, D is pile outer diameter)

piles recover to the non-soil plug removed pile after 100 mm penetration depth. In Fig. 9(b), the loading curves of the soil plug removed piles, particularly after 1.0*D* case, are towards the non-soil plug removed pile, hence, reaching it after some penetration depth. Although the results in this paper are from a limited number of model tests, we can conclude that the effective length of the soil plug depends on the sleeve height of the inner-sleeved piles, and it is roughly two times the pile outer diameter (*i.e.*, 2*D*).

3.3 Plug Length Ratio and Incremental Filling Ratio

Two indexes widely used to describe the degree of soil plugging of open-ended piles, called plug length ratio (PLR) and incremental filling ratio (IFR) are defined in Eqs. (10) and (11) respectively (Paikowsky *et al.* 1989; Paik and Lee 1993). The PLR indicates an average behaviour of plugging state for a long penetration depth. In contrast, the IFR indicates the instantaneous plugging state at small penetration depth. As plug condition may change discontinuously with pile penetration, the IFR is a better indication of plugging condition than the PLR.

$$PLR = \frac{h}{H} \tag{10}$$

where *PLR* is plug length ratio, *h* is soil plug height and *H* is penetration depth (see Fig. 5).

$$IFR = \frac{\Delta h}{\Delta H} \times 100\,(\%) \tag{11}$$

where *IFR* is incremental filling ratio, Δh is the change of soil plug height for penetration depth of ΔH (see Fig. 5).

It should be noted that the plug length ratio and incremental filling ratio have been defined for the non-sleeved piles. Therefore, the measured soil plug height should be corrected to evaluate them for the sleeved-piles. The corrected soil plug height, h_{cor} was calculated assuming that the soil volume of a sleeved pile is equal to its virtual non-sleeved pile as given in Eqs. (12) and (13) when the soil plug height, *h* is less than and more than the sleeve height, *l*, *i.e.*, $h \le l$ and $h > l$, respectively.

$$h_{\mathrm{cor}} = \left(\frac{d_{\mathrm{s}}}{d_{\mathrm{ns}}}\right)^2 h \quad \text{for} \quad h \le l \tag{12}$$

where h_{cor} is the corrected soil plug height, d_s is pile inner diameter of a sleeved pile, d_{ns} is pile inner diameter of its virtual non-sleeved pile (see Fig. 10 for the definition), *h* is the measured soil plug height and *l* is sleeve height.

$$h_{\mathrm{cor}} = (h - l) + \left(\frac{d_{\mathrm{s}}}{d_{\mathrm{ns}}}\right)^2 h \quad \text{for} \quad h > l \tag{13}$$

where h_{cor} is the corrected soil plug height, d_s is pile inner diameter of a sleeved pile, d_{ns} is pile inner diameter of its virtual non-sleeved pile (see Fig. 10 for the definition), *h* is the measured soil plug height and *l* is sleeve height.

The PLR and IFR were then evaluated using the corrected soil plug height. Figures 11(a) and 11(b) show the measured and corrected soil plug heights versus penetration depth respectively.

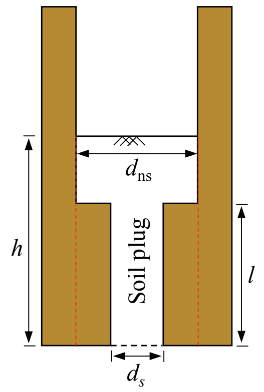


Fig. 10 The definition of the inner diameter of a virtual non-sleeved pile

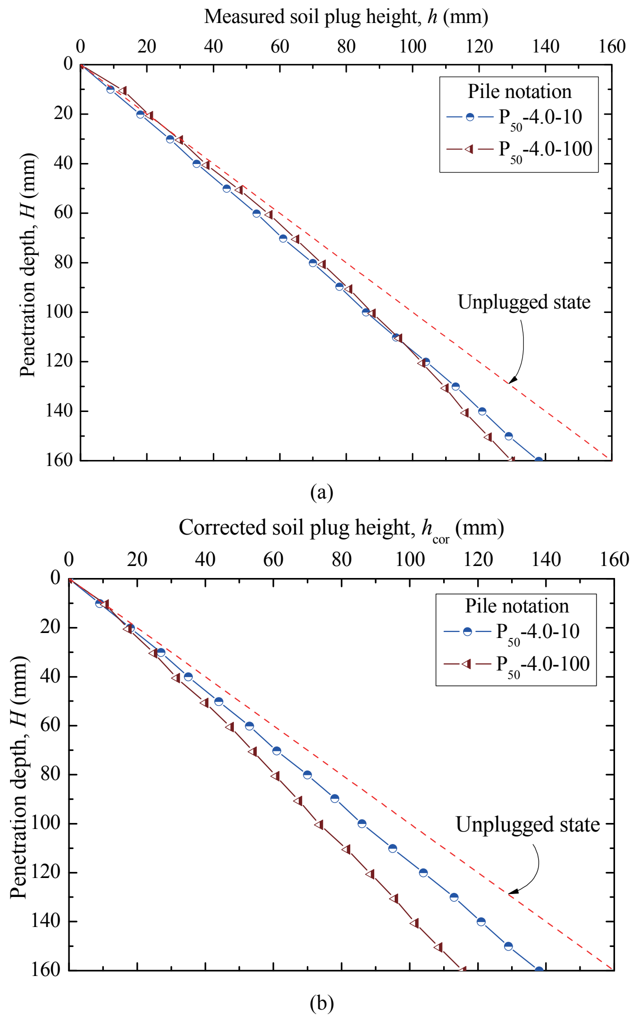


Fig. 11 (a) Measured and (b) corrected soil plug height versus penetration depth

Figures 11(a) and 11(b) indicate that the piles with a higher sleeve height produce a higher degree of soil plugging (*i.e.*, away from the unplugged state). It should also be noted that although the variation of the soil plug heights in Fig. 11(a) is relatively small, Fig. 11(b) shows that the sleeve height influences the soil plug height with a clear variation between the two piles. Figures 12(a) and 12(b) show the results of the original and corrected incremental filling ratio versus penetration depth respectively.

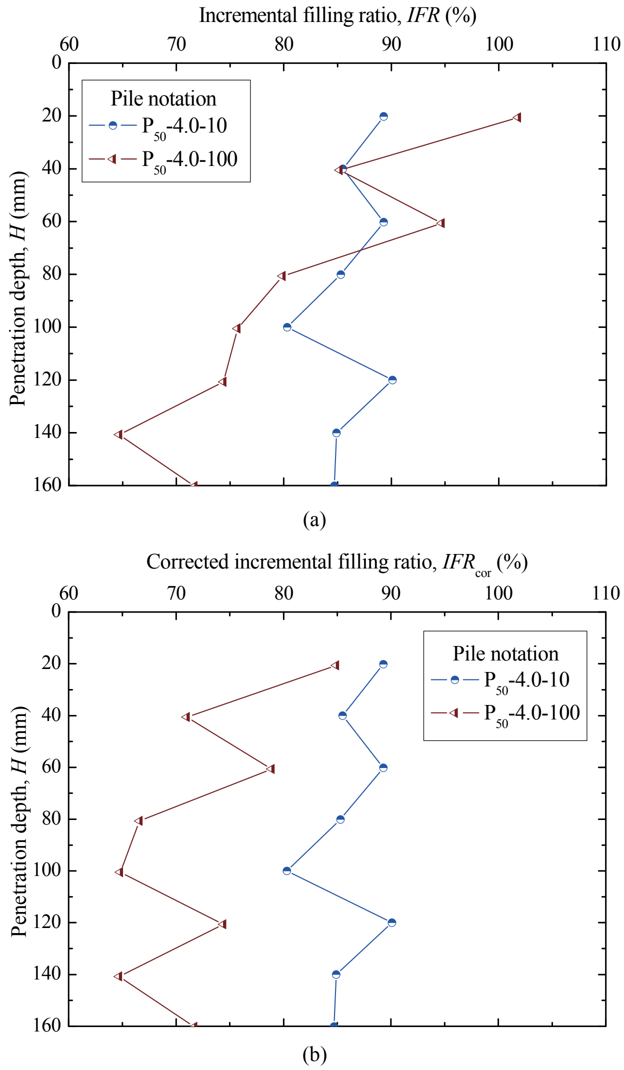


Fig. 12 (a) Original and (b) corrected incremental filling ratio versus penetration depth

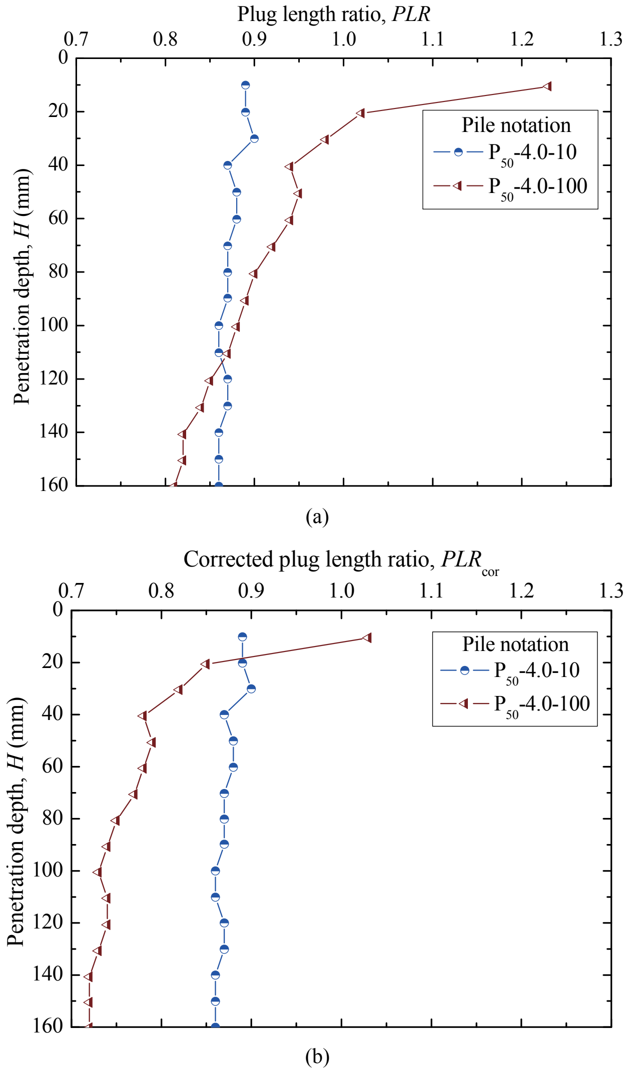


Fig. 13 (a) Original and (b) corrected plug length ratio versus penetration depth

The incremental filling ratio, *IFR* was calculated at 20 mm intervals in this paper although the measurements were taken at 10 mm intervals to reduce scattering of the data. A comparison of the two piles with different sleeve heights indicate that the sleeve height affects the degree of soil plugging (see Figs. 12(a) and 12(b)), where it clearly shows that a pile of a higher sleeve height produces a higher degree of soil plugging (*i.e.*, smaller values of *IFR*). The results of Figs. 12(a) and 12(b) also indicate that the corrected *IFR* gives better indication of the soil plugging, particularly at shallow depth (or where the penetration depth is equal to the sleeve height). Figures 13(a) and 13(b) show the results of the original and corrected plug length ratio versus penetration depth respectively. As shown for the soil plug height in Fig. 11(b), Fig. 13(b) also shows a clear difference of the plug length ratio between the two sleeved-piles than Fig. 13(a) when the plug length ratio is corrected for its virtual non-sleeved pile. Figure 13(b) also show that the realistic value of the plug length ratio (*i.e.*, less than 1.0) is well indicated by the corrected plug length ratio at early penetrations. As mentioned earlier, the plug length ratio indicates the average behaviour of the soil plugging over a large penetration depth. Therefore, we can say that the piles with a higher sleeve height produce, on average a higher degree of soil plugging.

4. CONCLUSIONS

In this paper, the effective length of the soil plug was studied using small-diameter sleeved piles penetrated into a medium-dense sandy ground. At first, the effects of the sleeve heights on the bearing capacity, in particular inner frictional resistance was discussed using a simple analysis method. The results suggest that a higher sleeve height increases the bearing capacity due to the increase in inner frictional resistance. A series of model experiments conducted by removing the generated soil plugs reveal that, not only the sleeve height affects the penetration resistance, but also the effective soil plug length is roughly two times the pile diameter. The experiments also indicate that the penetration of the soil plug removed piles do not recover to the non-soil plug removed pile when the sleeve height is quite small (*i.e.*, 10 mm of the piles tested in this study). The results of the soil plug heights suggest that it is influenced by the sleeve height. The results of incremental filling ratio and plug length ratio were also discussed. The incremental filling ratio and plug length ratio of the sleeved-piles were evaluated using a new simple method to ensure that the originally defined equations for the non-sleeved piles are compatible with the sleeved piles. The results of the corrected incremental filling ratio and plug length ratio give a better indication on the soil plugging, particularly at the early penetration depths.

ACKNOWLEDGMENTS

The financial assistance to the first author by President Postdoctoral Fellowship, Tokyo University of Science, Japan is highly appreciated. The financial supports provided by The Japan Iron and Steel Federation (JISF) and International Press-in Association (IPA) are also acknowledged. The contribution during laboratory experiments by Mr. Takahiro Yajima, a former undergraduate student at Tokyo University of Science is also appreciated.

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