14 Apr 2004, 4:30 pm - 6:30 pm

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

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ABSTRACT

Both the driving response and static bearing capacity of open-ended piles are affected by the soil plug that forms inside the pile during pile driving. In order to investigate the effect of the soil plug on the load capacity of pipe piles in general, field pile load tests were performed on instrumented open- and closed-ended piles driven into sand. For the open-ended pile, the soil plug length was continuously measured during pile driving, allowing calculation of an incremental filling ratio, IFR for the pile. The cumulative hammer blow count for the open-ended pile with final IFR of 77.5% was 16% lower than for the closed-ended pile. The limit unit shaft and base resistances of the open-ended pile were 51% and 32% lower than the corresponding values for the closed-ended pile. It was also observed, for the open-ended pile, that the unit soil plug resistance was only about 28% of the unit annulus resistance.

INTRODUCTION

Pipe piles can be either open-ended or close-ended. It has been documented that the behavior of open-ended piles is different from that of closed-ended piles (Szechy, 1961; Randolph et. al., 1979; Klos and Tejchman, 1981; Paikowsky and Whitman, 1990; Lee et al., 2003). According to the field test results of Szechy (1959), the blow count necessary for driving a pile to a certain depth in sands is lower for an open-ended pile than for a closed-ended pile. Thus, it is generally acknowledged that an open-ended pile requires less installation effort than a closed-ended pile under the same soil conditions.

It is also known that an open-ended pile has lower load capacity than an equivalent closed-ended pile at shallow penetration depth. However, as penetration depth increases, the load capacity of the open-ended pile approaches that of the equivalent closed-ended pile. This is due to the greater degree of soil plugging with larger penetration depth (Klos and Tejchman, 1981; Paikowsky and Whitman, 1990). According to Szechy (1961), the settlement of an open-ended pile is greater than that of a closed-ended pile under the same load and soil conditions. This means that the load capacity of open-ended piles at the same settlement is typically lower than that of closed-ended piles. However, the difference in load capacities varies within a wide range, depending on the degree of soil plugging during driving. Despite the overwhelming impact of soil plug formation on pile capacity, most design criteria do not satisfactorily consider the soil plug contribution to the load capacity of open-ended piles.

In order to study the load capacity of open-ended piles bearing in sand, both an open-ended and a closed-ended pipe pile with a diameter of 356 mm were driven to roughly the same depth (7 m) at the same site. The piles were fully instrumented before driving, and load-tested to failure. Pile Driving Analyzer (PDA)[tm] tests were performed during driving. The open-ended pile was assembled and instrumented in a way that allowed measurement of the soil plug length during pile driving, measurement of the friction between the soil plug and the inner surface of the pile, and separation of the contributions of annulus resistance and soil plug resistance to total base resistance. These test results are described and analyzed in this paper.

SITE DESCRIPTION

The test site is located on the south side of a bridge construction site over the Pigeon River at Lagrange County in Indiana. Approximately 2 m of the fill material around the test piles were removed before site investigation and pile driving. SPT and 2 CPTs (C_1 for closed-ended pile and C_2 for open-ended pile) were conducted before pile installation. From SPT split soil samples, the soil at the test site is known to be predominantly gravelly sand. The SPT and CPT results also indicate that the first 3 meters of the gravelly sand deposit are in a loose state, while the rest of the deposit down to a depth of 13–14 m is in dense to very dense state, with SPT N values ranging from 20 to 60, and q_c, from 15 to 25 MPa.

The maximum and minimum dry unit weights of the gravelly sand were 18.64 kN/m^3 and 15.61 kN/m^3, respectively. The specific gravity (G_S) was 2.67, and the critical-state friction angle measured from triaxial compression tests was 33. Grain size analysis shows the gravelly sand to contain no fines.

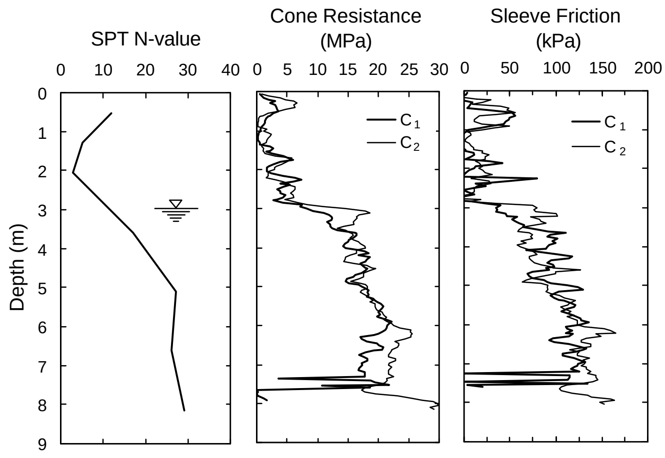


Fig.1. SPT and CPT results at test site

EXPERIMENTAL PROCEDURES

Test Pile Details and Instrumentation

The load capacity of closed-ended piles consists of two components: base and shaft resistances. For open-ended pipe piles, base capacity is composed of plug, annulus and shaft resistances. (Paikowsky and Whitman, 1990). Therefore, in this study, the closed-ended pile was instrumented using strain gauges to separate base and shaft resistances from the total load. For open-ended piles, the instrumented double walled pile system (Paik and Lee, 1993; Paik et al., 2003) was used to separate all the resistance components of the pile.

The closed-ended test pile had an outside diameter of 356 mm, wall thickness equal to 12.7 mm, and length equal to 8.24 m. Eighteen strain gauges were attached directly opposite each other at nine levels along the pile shaft, as shown in Fig. 2(a). Strain gauges were placed closer together near the pile base, since the load transfer rate tends to be higher in that part of the pile.

The open-ended test pile was assembled by combining two pipe piles with different diameters. The outside diameters of the outer and inner pipes were 356 mm and 305 mm, respectively; both had the same wall thickness of 6.4 mm. Twenty strain gauges were attached at ten different elevations to the outside surface of the inner pipe so as to separate the base resistance into plug and annulus resistances. Eighteen strain gauges were also attached to the outside surface of the outer pipe (i.e., pile shaft) at nine different elevations to measure the distribution and magnitude of the shaft resistance. The detailed configuration of the instrumentation for the open-ended pile is shown in Fig. 2(b). All strain gauges attached to both test piles were sealed with silicon, and then covered with an angled steel plate. After completion of strain gauge installation, the inner pipe was inserted into the outer pipe. The assembled open-ended pile had outside and inside diameters of 356 mm and 292 mm, and length equal to 8.24 m, the same length as for the closed-ended pile.

In order to measure the soil plug length during pile driving, two

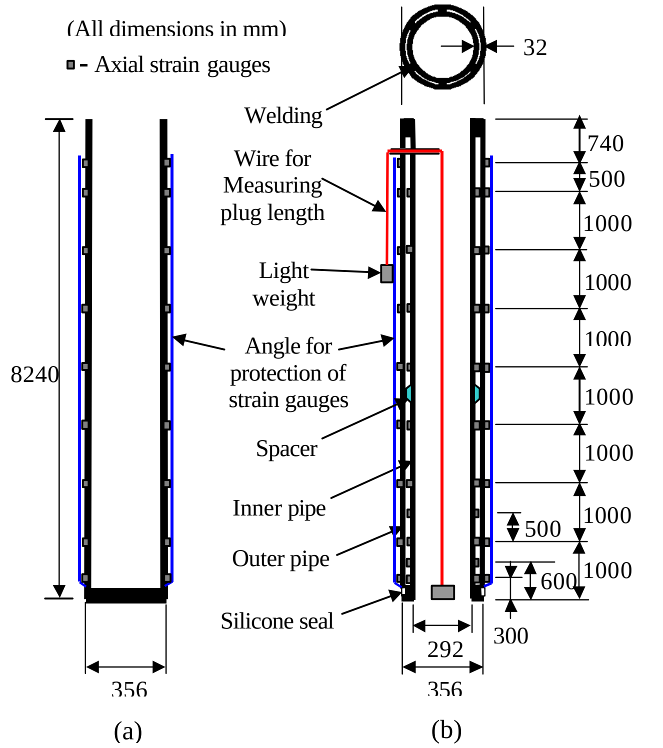


Fig. 2. Schematic of test piles: (a) closed-ended pile and (b) open-ended pile

different weights were used. The weights were connected to each other by means of a steel wire. The heavier weight was placed inside the pile and rested on top of the soil plug during pile driving. The lighter weight was hung outside the pile. This allowed measurement of the soil plug length by referring to the location of the lighter weight during pile driving (see Fig. 2(b)). A gap of 30 mm between the outer pipe and the pile toe prevented the base resistance from being transferred to the outer pipe. This gap was sealed with silicon to avoid intrusion of soil particles into the gap during pile driving.

The values obtained from the strain gauges were transformed into loads using the elastic load-strain relations for each pile. The base resistance of the open-ended pile was measured from the strain gauges on the inner pipe. The annulus and plug resistances were estimated under the assumption that unit frictional resistance between the pile and soil plug is the same between the lowest strain gauge and the pile base as it is between the lowest and second lowest strain gauge. The shaft resistance of the open-ended pile was obtained from the strain gauges attached to the outer pipe. The base resistance of the closed-ended pile was also estimated by assuming the unit shaft resistance to be the same between the last strain gauge and the pile base as between the two lowest strain gauges.

Pile Driving and Dynamic Testing

The open- and closed-ended piles were driven using a single-acting diesel hammer, which has a rated maximum driving energy of 56.8 kN m (kJ). The open- and closed-ended piles were driven to depths of 7.04 m and 6.87 m, respectively.

Because the ground surface at the test site slopes gently, the pile base was at the same level for both piles. During pile driving, the hammer blow count necessary for driving the test piles was recorded to investigate the drivability of similar closed- and open-ended piles under the same driving energy and soil conditions. As shown in Fig. 3, the soil plug length during pile driving was also measured continuously using the two weights described earlier. This allows calculation of the incremental filling ratio, IFR, which is defined as the increment in soil plug length per unit increase of penetration depth.

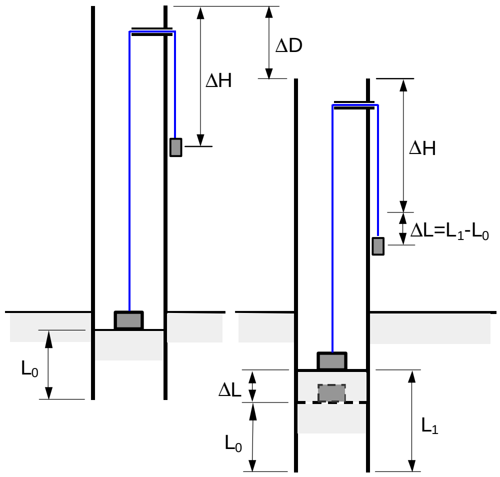


Fig. 3. Measurement of soil plug length during pile driving

Dynamic load tests were performed on both piles both during driving and during the re-striking, 8 days after completion of the static load tests. The delivered energy during the series of blows ranged from 19.0 to 28.5 kN m and caused the permanent displacement per blow of the piles to vary from 9 mm to 15 mm per blow. The pile capacities of both the closed- and open-end piles were estimated by GRL and Associates (2000) based on signal matching analysis using CAPWAP.

Static Load Tests

The total load applied to the pile head during each static load test was measured by a load cell with a capacity of 2.0 MN. The vertical settlement of the pile head was measured by two dial gauges attached to reference beams with supports placed at least 6.8 pile diameters away. The values of all strain gauges attached to both test piles were re-zeroed both before pile driving and at the start of the load tests in order to independently measure both the residual loads after pile driving and the loads induced along the length of the test piles during the load tests. The soil plug length was measured both before and after the static load tests in order to detect any possible change of IFR.

The load was applied to the test pile in increments of 147 kN; this increment was reduced to 49-98 kN near the end of the test. Each load was maintained until the settlement rate stabilized at less than 0.5 mm/hr. Strain gauge measurements were taken for every loading step at the time of settlement stabilization. The static load tests were continued until the pile settlement reached about 146-152 mm (about 42% of the outside pile diameter) for both the open- and closed-ended piles.

Determination of Limit Load Capacity

The limit load capacity of both test piles were estimated by Chin's method (Chin, 1970), based on the assumption that the load-settlement relation is hyperbolic. Test results show that the shaft resistance reached a limit value well before the final load step, while the base resistance was still increasing at the final load step. Thus, the limit shaft load capacities of the closed- and open-ended piles were determined as those mobilized at the final load step. The limit total load capacity was obtained for each pile by adding the limit base load capacity estimated by the Chin's method to the measured limit shaft load capacity. In the case of the open-ended pile, the Chin extrapolation was done for the base load (Q_b), which is a summation of the plug load (Q_{plug}) and the annulus load (Q_{ann}). The resulting limit base capacity was then separated into a limit annulus capacity and a limit plug capacity in the same proportion as Q_{ann}/Q_{plug} for the last loading step of the pile load test.

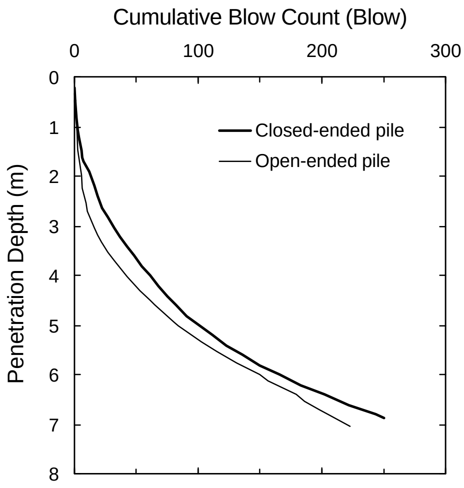
EXPERIMENTAL RESULTS

Driving Resistance

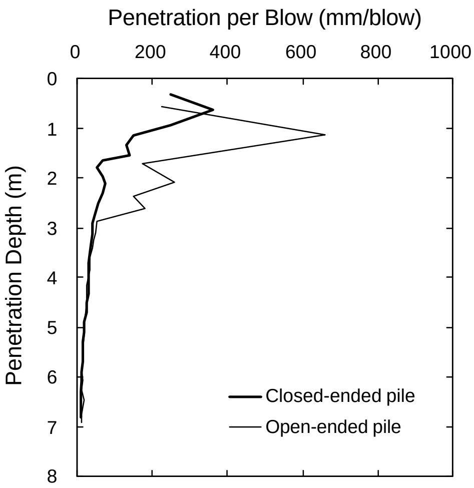
The hammer blow count required for driving the two test piles down to the final penetration depth and penetration depth per blow are plotted versus pile penetration depth in Fig. 4. It can be seen in Fig. 4(a) that the cumulative hammer blow count for the open-ended pile was consistently lower than that for the closed-ended pile. For a penetration depth of 6.87 m, which is the final penetration depth for the closed-ended pile, the cumulative blow counts were 250 and 211 blows for the closed- and open-ended piles, respectively. The difference in hammer blow counts between the open- and closed-ended piles was quite significant initially, but decreased gradually as the penetration depth increased. This is consistent with the results of Szechy (1959), who showed that the blow count required for driving open-ended piles approaches the blow count required for driving closed-ended piles with increasing penetration depth. This can be seen more clearly in Fig. 4(b), which shows penetration depth per blow vs. pile penetration depth. As shown in the figure, the penetration depth per blow for the open-ended pile was greater than for the closed-ended pile until a penetration depth approximately equal to 3.5m. After 3.5 m, which is about 10 times the outside pile diameter, the penetration rate for the open-ended pile is nearly the same as for the closed-ended pile. This can be attributed to the increase of penetration resistance for the open-ended pile due to the increasing degree of soil plugging with penetration depth.

Soil Plugging in the Open-Ended Pile

Formation of a soil plug in an open-ended pile is a very



(a)



(b)

Fig. 4. Driving record for open- and closed-ended piles: (a) blow counts versus penetration depth, and (b) penetration depth per blow versus penetration depth

important factor in determining pile behavior both during driving and during static loading. The degree of soil plugging can be represented by the incremental filling ratio (IFR), defined as

$$IFR = \frac{dL}{dD} \times 100 \ (\%) \quad (1)$$

where *dL/dD* expresses the increase of soil plug length *L* per unit increase of penetration depth *D*.

Fig. 5 shows changes of the soil plug length and IFR with penetration depth during pile driving. In the figure, the dashed line represents the fully coring driving mode for which IFR=100%. It can be seen from the figure that the IFR decreases sharply from 94.1% to 71.2% in the first 2.0 m of penetration and then increases to 88.3% at a penetration depth of about 4.0 m. As driving continues, IFR gradually decreases. At the final penetration depth, the IFR for the pile was 77.5%. These variations of IFR are closely linked with the relatively density of soil. Test results obtained from various chamber tests on open-ended piles showed that the IFR of piles driven into uniform sand gradually decreases with increasing penetration depth and with decreasing relative density (De Nicola and Randolph, 1997). Based on these results, the abrupt change of IFR near the penetration depth of about 2 m shown in Fig. 5 is due to the change of relative density at that depth. This can be confirmed by the relative density of the sand as estimated using the results of CONPOINT (Salgado et al. 1997), a program that allows calculation of the relative density of soil based on the CPT results. The estimated relative densities were about 30% for the first 3 m and about 80% for depths greater than 3 m.

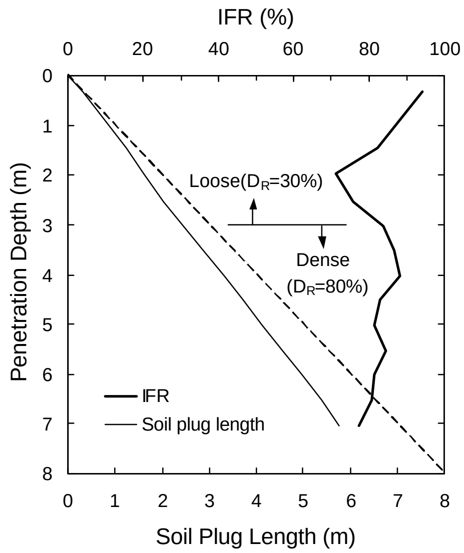


Fig. 5. IFR and soil plug length versus penetration depth for open-ended pile

Since the soil plug length was measured both before and after the static load test, it was possible to ascertain that there was not a change in the soil plug length as a result of the static load test. This result confirms the finding of Paik and Lee (1993), who showed that open-ended piles behave as fully plugged piles in static loading, regardless of the values of IFR achieved at the end of driving. This reinforces the fact that soil plug behavior is very different under dynamic and static penetration conditions.

Residual loads

Piles are driven by repeated hammer blows, which subject each cross section of the pile to a sequence of compression/tension pulses. At the end of the last hammer blow, the pile reaches static equilibrium. There always are residual loads left in the pile; these are always compressive at the pile base. For equilibrium to be established, the upward (compressive) residual base load must equal the downward resultant of the residual shaft loads.

Residual loads in both test piles were measured by reading the values of the strain gauges after pile driving (the strain gauges are zeroed before pile driving). Fig. 6 shows the distributions of residual loads measured along the closed-ended pile (CEP) and the inner and outer pipes of the open-ended pile (OEP). In the figure, Q_{rb} is the residual base load for both the open-ended and the closed-ended piles, Q_{rp} is the residual soil plug load for the open-ended pile, and Q_{ra} is the residual annulus load for the open-ended pile.

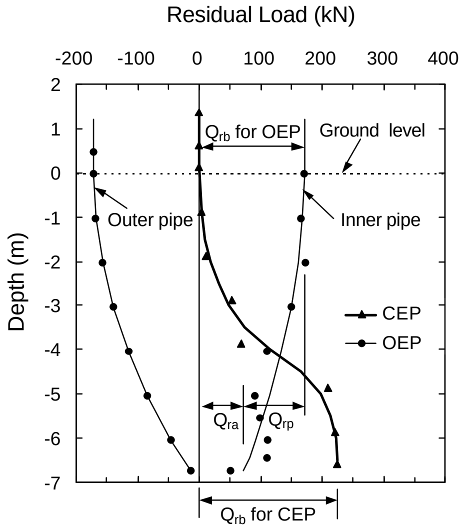


Fig. 6. Load distribution curves for residual loads

The residual base loads of the open- and closed-ended piles are 171 kN and 225 kN, respectively. These residual loads equal 24% and 26%, respectively, of the base load at a settlement corresponding to 10% of the outer pile diameter for each pile. For the open-ended pile, the residual plug and annulus loads estimated from the load distribution along the inner pipe are 108 kN and 63 kN, respectively, corresponding to 41% and 14% of the plug and annulus loads at a settlement of 10% of the pile diameter. Measurement of the residual load distribution along the outer shaft was not possible due to uncertainties in the readings due to drift of the strain gauge values. Therefore, the residual load distribution along the outer shaft of the open-ended pile was obtained under the assumption that the distribution of unit shaft resistance is triangular and fully balances the sum of the residual plug and annulus loads, as is required by equilibrium considerations.

Darrag (1987) reported that the magnitude and distribution of residual loads are affected by the total load capacity of the pile, the ratio of shaft to total load capacity, the pile material (i.e., the pile axial stiffness), and the length and cross-sectional area of the pile. Our test results indicate that the residual load in the closed-ended pile is greater than that in the open-ended pile. Given that the pile material, length and gross cross-sectional area of both test piles are the same, the different residual loads are due mostly to the difference in compaction of the soil around the pile during driving caused by the difference in the cross sections of the two piles.

If the goal of a load test is simply to assess the total load capacity of a given pile, residual loads should not be taken into account, as they do not affect the total load capacity of the pile (the summation of residual shaft and base loads for the pile must equal zero). However, it would be conceptually correct to account for residual loads if the purpose of the load testing is to establish base and shaft unit resistances for use in designing other piles installed under conditions different from those prevailing for the load-tested piles.

The previous discussion suggests that if residual loads are not considered in the interpretation of compressive load test results for driven piles, the base load capacity may be underestimated and the shaft load capacity may be overestimated for other piles under compressive loads (Kraft, 1991). However, given the difficulties involved in either measuring or estimating residual loads in practice, caution is in order when attempting to account for residual loads in design. The permanent load capacity that would be available to support structural loads for the two piles load-tested for this research does not include the residual loads; in this paper, test results are reported accordingly. However, all the information the reader needs to account for residual loads in calculations involving the load test results presented here is provided in Fig. 5. Additionally, we do provide values both including and not including residual loads for the quantities most likely to be used in design (such as limit unit resistances).

Load-Settlement Response

Fig. 7 shows the load-settlement curves for both test piles obtained from the static load tests and CAPWAP analyses. It is observed that the settlement of the open-ended pile is always greater than that of the closed-ended pile for any given load. This is expected, as the closed-ended pile is a full-displacement pile, while the open-ended pile was installed under conditions of partial plugging. The maximum loads applied to the open- and closed-ended piles in the static load tests were 1.28 MN and 1.77 MN, respectively. The limit load capacities of the open- and closed-ended piles estimated by Chin's method were 1.33 MN and 1.86 MN, respectively.

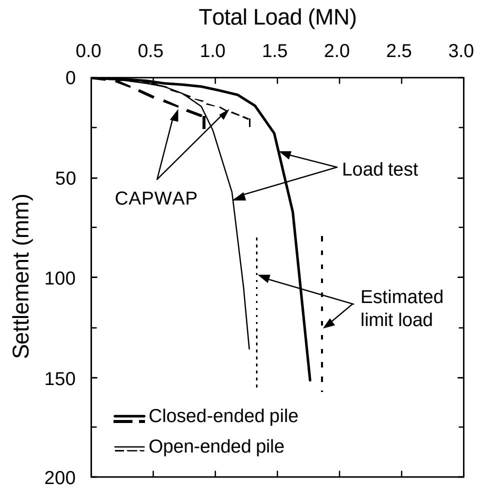


Fig. 7. Load-settlement curves for static and dynamic load tests

The load-settlement curves by CAPWAP analysis were somewhat in contrast with what was observed in the static load tests. The pile capacity predicted by the CAPWAP analysis was 1.28 MN for the open-ended pile and 0.90 MN for the closed-ended pile. These CAPWAP predictions are based on the re-strike tests. The load-settlement curve estimated using CAPWAP for the open-ended pile is stiffer than that estimated for the closed-ended pile. This is not consistent with either the observations from the load tests or with the expected load response of open vs. closed-ended piles. It is likely that the CAPWAP pile capacity estimated for the open-ended pile is not reliable because the pile is double-walled. The CAPWAP pile capacity for the closed-ended pile was also off, corresponding to only 51% of the load at the end of the static load test, an estimate that is clearly conservative.

Base and Shaft Load Capacity

In the static load test on the closed-ended pile, the load was applied in eleven increments taking the load to 0.29, 0.44, 0.59, 0.74, 0.88, 1.03, 1.18, 1.32, 1.47, 1.62, and 1.77 MN. The load distribution along the test pile length is shown in Fig. 8 for each load step. For the final load step, the load distribution including residual loads is also plotted as a dotted line. It is seen from the figure that the load applied to the pile is mainly supported by shaft resistance for initial loading stages. The load is then gradually transferred to the pile base. It is also found that most of the shaft resistance is developed along the lower 3.0 m of the pile.

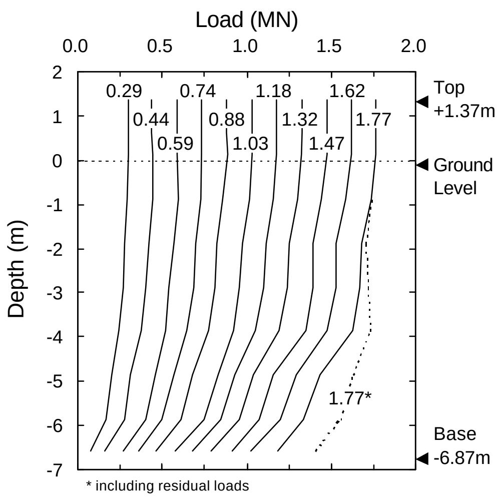
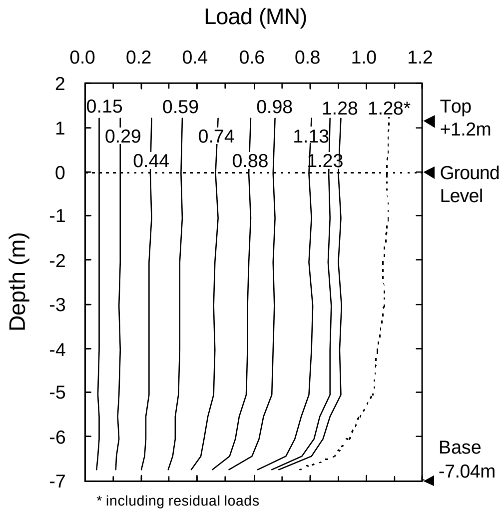
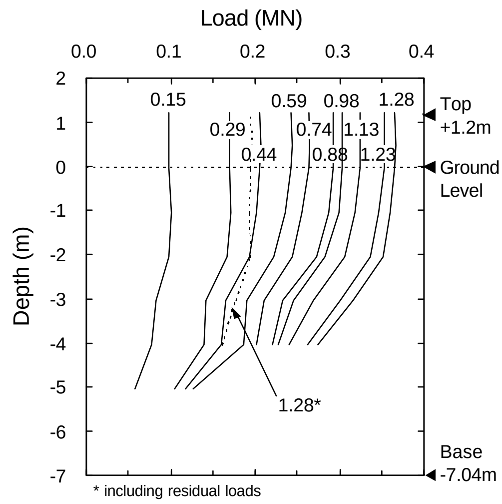


Fig. 8. Load distribution curves for closed-ended pile

Fig. 9 shows the load distributions for the inner and outer pipes of the open-ended pile. The load distribution in the inner pipe, shown in Fig. 9(a), represents changes of transferred load along the soil plug, while the load distribution in the outer pipe, shown in Fig. 9(b), shows the distribution of the shaft resistance. Some of the strain gauges at the lower part of the outer pipe were damaged during pile driving, and the interrupted shaft resistance distributions for some of the load steps reflect this. The load distributions in the inner and outer pipes were measured for the loading steps corresponding to applied loads equal to 0.15, 0.29, 0.44, 0.59, 0.74, 0.88, 0.98, 1.13, 1.23, and 1.28 MN. As shown in Fig. 9(a), the total base load was solely supported by the annular area, with nearly zero soil plug resistance mobilized, up to the 0.59MN loading step. For loads greater than 0.74 MN, some of the applied load was transferred to the soil plug. It is also observed that, for the final load increments, most of the soil plug resistance was mobilized within a distance of 6.8 times the inside pile diameter measured from the pile base.



(a)



(b)

Fig. 9. Load distribution curves: (a) for base resistance of open-ended pile, and (b) for shaft resistance of open-ended pile

Table 1 shows both measured and estimated values of the total, base and shaft load capacities of both test piles. It also has the soil plug and annulus capacities of the open-ended pile. Specifically, the table contains, for each test, the loads at the end of the test, the loads extrapolated using Chin's method, the loads both including and not including residual loads at a settlement equal to 10% of the pile diameter, and the CAPWAP predictions based on re-strike. It is found from Table 1 that the limit base

Table 1. Summary of measured and estimated key load capacities

Parameters	Closed-ended pile			Open-ended pile				
	Total	Base	Shaft	Total	Base	Plug	Annulus	Shaft
Load at end of static load test (kN)	1765	1115	650	1275	909	336	573	366
Load at settlement of 10% of pile diameter (kN)[a]	1499	866	633	1025	715	265	450	310
Load at settlement of 10% of pile diameter (kN)[b]	1499	1091	408	1025	886	373	513	139
Limit load capacity by Chin's method (kN) [a]	1861	1211	650	1333	967	358	609	366
Limit load capacity by Chin's method (kN) [b]	1861	1436	425	1333	1138	421	717	195
CAPWAP prediction based on re-strike test (kN)	903	752	151	1277	823	–	–	454

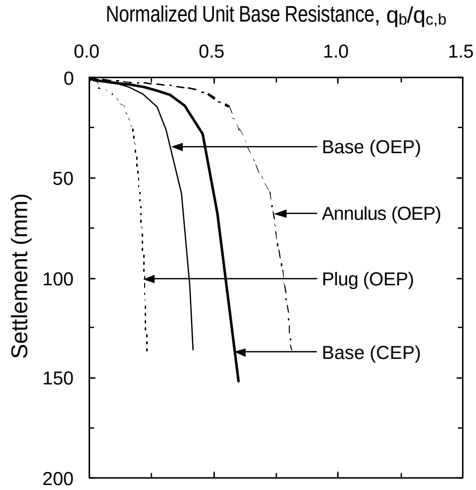
a: not accounting for residual loads, b: accounting for residual loads

and shaft loads for the closed-ended pile are 25% and 78% larger than for the open-ended pile, respectively. When taking the load at a settlement of 10% of the pile diameter as the pile load capacity, the base and shaft load capacities for the closed-ended pile are then 21% and 104% larger than for the open-ended pile, respectively. The higher base and shaft resistances of the closed-ended pile, compared with the open-ended pile, are due to the large differences in the installation of the two piles. The closed-ended pile is clearly a full-displacement pile, which considerably pre-loads the soil beneath and around it. The open-ended pile was installed without a significant degree of plugging and without pre-loading the soil around it to any significant extent. It behaves more as a small-displacement than as a full-displacement pile, with accordingly lower shaft and base load capacities.

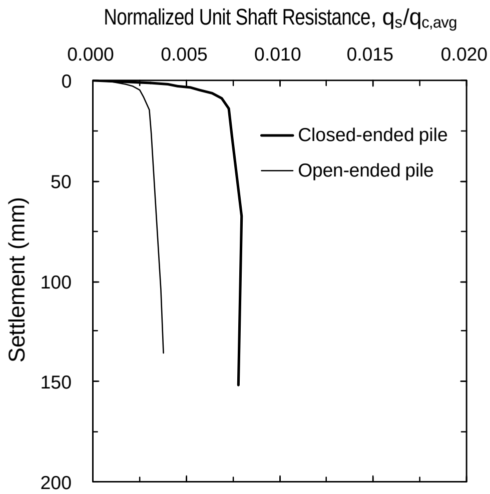
Bearing Capacity Comparison for the Open- and Closed-Ended Piles

Fig. 10 shows the normalized unit resistance-settlement curves for the base and shaft of both test piles. In this figure, in order to eliminate the differences in pile load capacities that might be caused by the differences between soil properties (as evidenced by the slightly different CPT cone resistance profiles at C_1 and C_2, as shown in Fig. 1), the unit base and shaft resistances were normalized with respect to average values of base and shaft cone resistances, $q_{c,b}$ and $q_{c,avg,}$ respectively. The average base cone resistance ($q_{c,b}$) used for normalizing unit base resistance was defined for each pile as the average q_c value from the corresponding CPT test from the pile base to 2 pile diameter below the pile base. The average shaft cone resistance ($q_{c,avg}$) for normalizing unit shaft resistance was calculated along the whole length of each pile.

As shown in Fig. 10(a), the normalized unit base resistance for the open-ended pile (OEP) was 0.42, 28% lower than the 0.58 observed for the closed-ended pile (CEP) at a settlement of 140 mm. However, the annular area in the open-ended test pile was approximately 33% of the gross cross-sectional area of the pile. This is significantly greater than the typical 11% for conventional open-ended pipe piles. Accordingly, in practice, the difference between the base loads of geometrically similar open- and closed-ended piles installed in the same soil to the same depth would be more pronounced because the unit annulus resistance is significantly higher than the unit soil plug resistance.



(a)



(b)

Fig. 10. *Comparison between normalized unit base and shaft resistances of open- and closed-ended piles: (a) normalized unit base resistance, and (b) normalized unit shaft resistance*

It is also seen in Fig. 10(a) that the unit annulus resistance of the open-ended pile is higher than the unit pile base resistance of the closed-ended pile. The unit annulus resistance of the open-ended pile and the unit base resistance of the closed-ended pile at a settlement of 140 mm are about 81% and 58% of the average

Table 2. Summary of Normalized Unit Resistance

Unit resistance normalized with respect to q_c	Residual Loads	Closed-ended pile		Open-ended pile			
		Base	Shaft	Base	Plug	Annulus	Shaft
Based on load at settlement of 10% of pile diameter	not included	0.47	0.0076	0.33	0.18	0.64	0.0032
Based on load at end of static load test	not included	0.60	0.0078	0.42	0.23	0.81	0.0038
Based on load estimated by Chin's method	not included	0.65	0.0078	0.44	0.24	0.86	0.0038
Based on load at settlement of 10% of pile diameter	included	0.59	0.0049	0.41	0.23	0.67	0.0014
Based on load at end of static load test	included	0.72	0.0051	0.50	0.28	0.84	0.0020
Based on load estimated by Chin's method	included	0.77	0.0051	0.52	0.29	0.89	0.0020

Note: base, plug and annulus resistances normalized with respect to $q_{c,b}$; shaft resistance normalized with respect to $q_{c,avg}$

cone resistance ($q_{c,b}$) values obtained from C_1 and C_2. The unit soil plug resistance is about one third of the unit annulus resistance. These results justify the assumption made by some authors (e.g., Lehane and Randolph, 2002) that the unit annulus resistance is approximately the same as the cone resistance at the same depth.

Fig. 10(b) shows that the normalized unit limit shaft resistance is, as discussed earlier, much greater for the closed-ended pile than for the open-ended pile, even though they have the same diameter and were installed to the same penetration depth. These were 0.0078 for the closed-ended pile and 0.0038 for the open-ended pile. This large difference is due to the different amounts of radial displacements experienced by the soil around the piles during pile driving, as discussed earlier, and is consistent with the finding of Randolph et al. (1979). The normalized unit base and shaft resistances for both test piles are summarized in Table 2.

Fig. 11 shows the traction between the soil plug and the inner surface of the pile as well as the unit outer shaft resistance (the traction between the pile and surrounding soils). As mentioned earlier, the unit soil plug resistance is smaller than the unit annulus resistance. However, the soil plug resistance develops only because sufficient friction develops between the soil plug and the inner surface of the pile. The unit inner shaft resistance was found to be greater than the unit outer shaft resistance, as shown in Fig. 11, except for small settlements. Physically, this can be understood as resulting from the higher contact stresses existing between the high compressed soil plug and the inner pile surface than those between the outer surface of the pile and the surrounding soil.

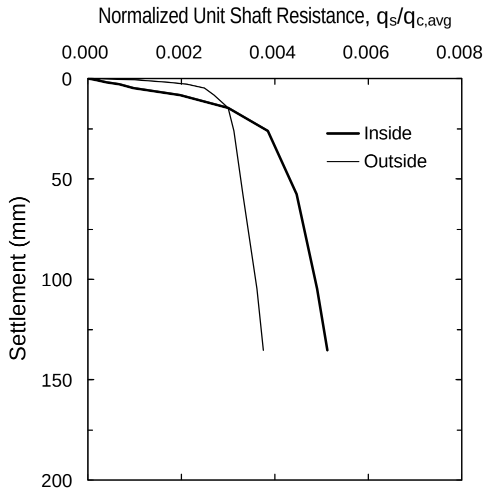


Fig. 11. Comparison between normalized unit inside and outside shaft resistances in open-ended pile.

SUMMARY AND CONCLUSIONS

Both open-ended and closed-ended pipe piles are often used in practice, but high-quality information available on the bearing capacity of these piles is very limited. The core of the present study was the pile load tests done on open- and closed-ended piles driven into sand. The information generated by the load tests is particularly useful for engineers interested in the design of open-ended pipe pile in sand, as detailed data was collected on soil plug formation during driving and on static plug resistance.

The open-ended pipe pile in this study was driven in a partially plugged mode. Measurement of the soil plug length during driving permitted calculation of the IFR as a function of penetration depth. It was found, by comparison with the CPT cone resistance profile, that the IFR increased when the relative density of the sand also increased. It was also observed that the cumulative blow count was lower to drive the open-ended pile than the closed-ended pile to the same depth, but that the difference was mostly due to the early stages of driving, when the soil plug was not well developed.

The open- and closed-ended test piles were instrumented in a way that allows separation of all the resistance components of pile load capacity (base and shaft resistances for the closed-ended pile; and annulus, plug, and shaft resistances for the open-ended pile) The unit base and shaft resistances of the open-ended pile at a settlement of 10% of pile diameter, normalized by average cone resistances, resulted 30% and 58% lower than the corresponding values for the closed-ended pile. For the open-ended pile, the unit plug resistance was only 28% of the unit annulus resistance, and the average shear stress between the soil plug and inner surface of the pile was 36% higher than the unit outside shaft resistance.

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