Integrity testing of a very large number of piles

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ABSTRACT: The determination of the load capacity of driven piles is subject to uncertainties associated with changes in soil state resulting from pile installation. In the present paper, the load capacity of both closed- and open-ended piles is related to cone penetration resistance qc through an experimental program using calibration chamber model pile load tests and field pile load tests. Based on test results, the normalized base resistance qb/qc was obtained as a function of the relative density DR for closed-ended piles, and of both the relative density DR and the incremental filling ratio IFR for open-ended piles. The shaft resistance of both closed- and open-ended piles was found to increase with increasing driving depth. The lower and upper bounds of qb/qc for closed-ended piles were also obtained based on results for non-displacement piles. It was found that qb/qc values observed for the closed-ended pile were approximately the same as the upper bound values, while the normalized plug resistance qplug/qc of the open-ended pile was found to be only slightly higher than values of qb/qc for non-displacement piles.

1 INTRODUCTION

Open-ended pipe piles are often used in piling practice. Open-ended piles cause less change in the soil state than closed-ended piles with the same diameter, but more so than non-displacement piles with the same diameter. A major difference between closed- and open-ended piles is the possible formation of a "soil plug" inside the open-ended pile during driving. If no soil entered the pile during installation, open-ended piles would behave exactly as closed-ended piles. As the soil enters the pile, frictional resistance (i.e., plug resistance) is mobilized between the soils and the inner surface of the pile, which is referred to as the soil plug resistance. The base resistance of open-ended piles is a combination of the soil plug resistance and the annulus resistance.

Numerous investigations of the behavior of open-ended piles have been conducted either experimentally or analytically (e.g., Paikowski and Whitman 1990, Randolph et al. 1991, Paik and Lee 1993, De Nicola and Randolph 1997). In this paper, the pile load capacity of both closed- and open-ended driven piles in sand are investigated using fully instrumented field pile load tests and calibration chamber pile load tests. The relationship between pile load capacity and CPT cone resistance is established based on the determination of cone penetration resistance q_c for the same conditions as in the tests. Values of pile resistances normalized with cone resistance are provided for various soil and driving conditions.

2 LOAD CAPACITY OF PIPE PILES

For both non-displacement and displacement piles, the total pile load capacity consists of shaft and base capacities, as given by:

$$Q_t = Q_s + Q_b \tag{1}$$

where Q_t = total pile load capacity; Q_s and Q_b = shaft and base load capacities. Closed-ended pipe piles are displacement piles. The behavior of open-ended piles is more complex, with a response generally intermediate between that of non-displacement and displacement piles.

When the pile is loaded statically, its capacity will depend on the response of the soil plug, in addition to resistances mobilized at the pile annulus and along the pile shaft. Thus, for open-ended pipe piles, (1) applies with the base capacity defined as:

$$Q_b = Q_{plug} + Q_{ann} \tag{2}$$

where:

- Q_b = base capacity;
- Q_{plug} = soil plug capacity; and
- Q_{ann} = annulus capacity.

Although the installation of open-ended piles imparts less change to the surrounding soil than closed-ended or full displacement piles, the soil conditions are certainly different from those before installation (Randolph et al. 1979, Nauroy and Le Tirant 1983). The unplugged or fully coring mode is commonly observed during the initial stages of pile driving. As penetration and formation of the soil plug continue, internal frictional resistance mobilizes between the inner pile surface and the soil plug, densifying the lower part of the soil plug. However, some soil continues to enter the pile, characterizing partially plugged driving. Finally, with further driving, soil intrusion is prevented by the now sufficiently high frictional resistance between the soil plug and inner pile surface and by the large soil plug stiffness. Driving at this stage is said to take place under fully plugged conditions. Such behavior of open-ended piles is often related to the incremental filling ratio IFR, defined as follows:

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

where dL/dD = increase of soil plug length L per unit increase of driving depth D. Accordingly, the fully plugged and fully coring modes correspond to IFR values equal to 0 and 100%, respectively.

3 EXPERIMENTAL PROGRAM

3.1 *Calibration chamber tests*

Calibration chamber tests have been used in several instances to investigate pile behavior (Ghionna et al. 1993, Salgado et al. 1998, Lee and Abreu 1995, 2001). Smith and Lee (1993) and Paik et al. (1994) conducted a series of calibration chamber tests for both open- and closed-ended driven piles. A total of 36 calibration chamber load tests on closed- and open-ended piles were performed (Paik and Lee 1993, Paik et al. 1994). The calibration chamber used in the tests has a diameter of 0.775 m and a height of 1.25 m. Four different pile base depths (250, 420, 590, and 790 mm) were used in the load tests. The sand was Han River sand, a uniformly graded silica.

From the tests, it was observed that both closed- and open-ended piles show increasing resistance as the driving depth increases. In terms of resistance magnitudes, the shaft resistances of closed-ended piles are much higher than the shaft resistances of open-ended piles at all settlements.

3.1.1 *Field pile load tests*

In order to investigate the load capacity of closed- and open-ended piles in sand, full-scale field load tests were performed on one pile of each type (Paik et al. 2002). The test site is located on State Road 9 in Lagrange County in Indiana, US. The site characterization showed that the soils of the site were predominantly gravelly sands down to a depth of 13 – 14m. The gravelly sand is underlain by a stiff till containing clays and silts. Two cone penetration tests (CPT) were performed at the test site. The cone penetration tests were done at the locations where the test piles were later installed.

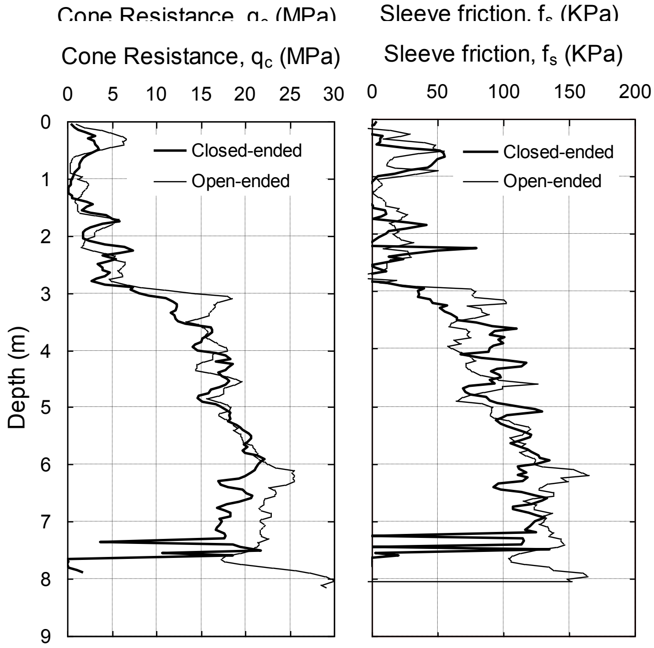


Figure 1. CPT results at field pile load test sites.

3.2 *Load-settlement response*

Fig. 1 shows the CPT results and the unit load-settlement responses of the pile base and shaft for the closed- and open-ended piles from field pile load tests. The base unit load q_b of the field open-ended pile was calculated by dividing the combined plug and annulus loads by the gross pile base area. The unit base resistance of the closed-ended pile at s/B = 0.10 (i.e., at a settlement of 10% of the pile diameter) is about 8.8 MPa, higher than the unit base resistance of the open-ended pile, which equals 7.2 MPa. The unit loads at the last loading stage (for which s/B ≈ 0.38) were 10.9 and 9.2 MPa for the closed- and open-ended piles, respectively.

In order to separate all the soil resistance components, the test piles were fully instrumented. For the open-ended pile, the double walled pile system, which allows measurements of the shaft, soil plug, and annulus resistances, was used. This system was also used for the model piles load-tested in the calibration chamber.

Fig. 2 shows the annulus and plug components of the unit base resistance for the open-ended pile. It is observed that, since unit loads were used in the figure, the annulus resistance was the highest of the two, equal to about 17.7 MPa at a settlement of 130 mm (s/B = 0.37). Based on the CPT sounding results given in Fig. 1, the annulus resistance at large s/B values appears to be quite close to the cone resistance q_c of about 21.9 MPa at the same depth. This is in agreement with the suggestion that the annulus resistance of open-ended piles be taken as equal to the cone resistance at the pile base depth (Lehane and Randolph 2002).

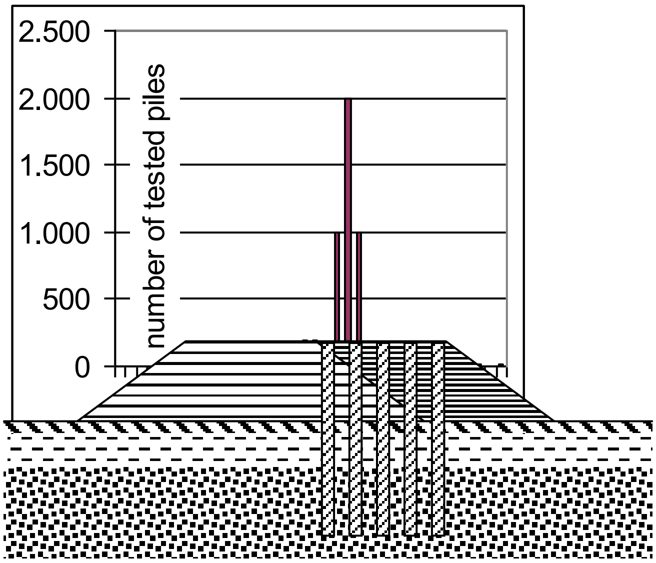
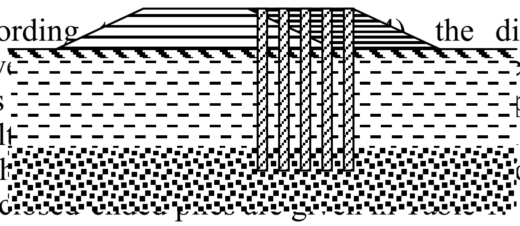


Figure 2. Base, plug, and annuls unit resistance from field open-ended pile load tests.

4 NORMALIZED PILE LOAD CAPACITY



According [...] the difference betw[...]n-ended piles [...]pth as a resul[...]ng with depth[...]or open- and c[...]

Table 1. Resistance ratio for closed- and open-ended piles as a function of driving depth (after Paik et al. 1994).

Driving depth (m)	Ratio of closed- to open-ended pile resistance: Base resistance	Shaft resistance
0.76	0.96	1.60
0.59	1.03	1.78
0.42	1.36	2.00
0.25	1.47	1.85

Since only one soil state was used for the closed-ended pile calibration chamber tests, the normalized resistances of closed-ended piles for various soil states were approximated using the resistance ratios of Table 1 and the experimental results for open-ended piles. Fig. 5(a), obtained in that fashion, shows that the value of q_b/q_c decreases as the relative density increases. For loose sands, with D_R equal to 23%, the value of q_b/q_c was in the 0.60-0.67 range, while for dense sand (D_R = 90%) it was in the 0.37 – 0.51 range. Likewise, Fig. 5(b) shows values of the normalized shaft resistance q_s/q_c. It is seen that closed-ended piles have higher values of q_s/q_c than observed for open-ended piles; these values range from 0.0049 to 0.0064 for loose and from 0.0042 to 0.0091 for dense sand.

4.1 *Normalized Pile Load Capacity from Field Pile Load Tests*

The normalized base resistance q_b/q_c for the closed- and open-ended piles at the last loading stage (i.e., s/B ≈ 0.4) are 0.58 and 0.42, respectively, while q_b/q_c = 0.47 and 0.32 for s/B = 0.1. The shaft resistances of the closed- and open-ended piles differed more markedly. The normalized shaft resistance for the closed-ended pile was equal to qs/qc = 0.0078, which is more than twice the value (0.0038) for the open-ended pile.

Fig. 3 shows the normalized load-settlement curves for the closed- and open-ended piles along with results by Lee and Salgado (1999a) for non-displacement piles (drilled shafts). In the figure, the lower and upper bounds define the range of values for normalized unit base resistance for driven piles (displacement piles) obtained from the q_b/q_c values for drilled shafts (non-displacement piles) multiplied by the base resistance ratios by DeBeer (1988) and Ghionna et al. (1993), respectively. The drilled-shaft base load-settlement curve in Fig. 3 is from Lee and Salgado (1999a) for σ'_v ≈ 100 kPa and D_R ≈ 90%, which is similar to the soil states for the field tests.

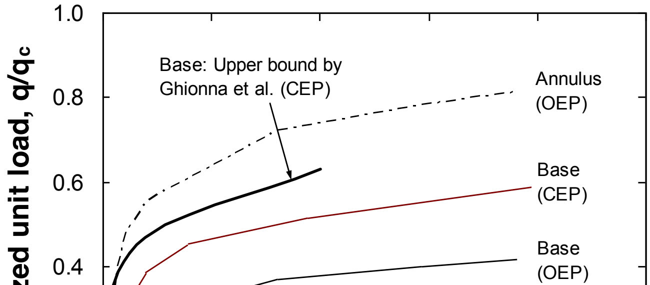


Figure 3. Normalized unit load versus settlement curves for closed-ended piles (CEP) and open-ended (OEP) piles compared with lower ad upper bounds of base resistance for driven piles.

As can be seen in the figure, the measured normalized unit base resistance of the closed-ended pile was close to the upper bound up to a relative settlement equal to s/B = 0.20. The normalized base resistance of the open-ended pile, on the other hand, falls between the upper and lower bounds. As individual components of the base resistance for the open-ended pile, the annulus and soil plug resistances are also plotted in the figure. The magnitude of the soil plug resistance is comparable to that of the lower bound base resistance (obtained for drilled shafts). This result suggests that, in design, the soil plug resistance for open-ended piles could be conservatively assumed to be equal to the base resistance of a drilled shaft.

5 CPT-BASED PILE RESISTANCE VALUES

For both closed- and open-ended piles, the total pile load capacity consists of the shaft and base resistances. Table 2 shows the values of the normalized unit shaft and base resistances for closed- and open-ended piles we propose for use in design. The values are proposed in terms of the relative density D_R and the incremental filling ratio IFR, respectively. The proposed values were obtained based on the results of the calibration chamber load tests and the field pile load tests described in earlier sections.

Table 2. Normalized pile resistance of closed- and open-ended piles.

	D_R (%)	IFR (%)	q_b/q_c	q_s/q_c
Closed ended piles	30	-	0.60	0.004 – 0.006
	50	-	0.56	0.004 – 0.006
	70	-	0.50	0.004 – 0.007
	90	-	0.42	0.004 – 0.009
Open-ended piles	-	40	0.60	0.0015 – 0.003
	-	60	0.40	0.0015 – 0.003
	-	80	0.27	0.0015 – 0.004
	-	100	0.20	0.0015 – 0.004

6 CONCLUSIONS

In this paper, the load capacities of both closed- and open-ended pipe piles were investigated based on results from calibration chamber tests and field pile load tests. Normalized pile unit resistances for both closed- and open-ended piles in terms of the cone resistance q_c were proposed.

A total of 36 calibration chamber and 2 full-scale field load tests on closed- and open-ended piles were analyzed. The base resistance of the closed-ended piles tested in the calibration chamber was found to be independent of the pile driving depth.

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