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BASE RESISTANCE OF OPEN-ENDED PILES EVALUATED BY VARIOUS DESIGN METHODS

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ABSTRACT: The design bearing capacity of an open-ended pile depends largely on the accuracy of the design method. Although the knowledge of shaft resistance has been understood quite well, the base resistance has not yet been completely understood due to the effects of soil plugging. The mechanisms of soil plugging is yet to be fully understood particularly for large diameter and long length piles installed in large construction projects. This paper compares the base resistance of two open-ended field piles constructed in the Tokyo Bay project evaluated by various design methods including cone penetration test (CPT)- and standard penetration test (SPT)-based methods. In total, five design methods including the conventional American Petroleum Institute (API) approach were included. In Japan, SPT-based design methods are used in practice. The CPT-based design methods, which are not popular in Japan were also included to evaluate their effectiveness. The CPT-design methods discussed in this paper classify open-ended piles into plugged or unplugged modes. The results reveal that the Fugro (i.e., CPT-based) and the API design methods overestimate the base resistance. In contrast, the ICP (i.e., CPT-based) and Port and Airport Research Institute (PARI) (i.e., SPT-based) design methods underestimate the base resistance. Based on the results, we can recommend the University of Western Australia (UWA) design method (i.e., CPT-based) as it produces the nearest results to the actual base resistance measured from the field load tests.

Keywords: Base Resistance, Cone Penetration Test, Design Methods, Open-Ended Piles, Soil Plugging

1. INTRODUCTION

Bearing capacity of open-ended piles is evaluated by various design methods including standard penetration test (SPT)- and cone penetration test (CPT)-based design methods. The bearing capacity of an open-ended pile consists of three components as given in Eq. (1) (see Fig. 1 too). The outer frictional resistance, q_{out} is often referred as shaft friction. The base resistance is produced by the summation of plug resistance and annulus resistance (see Eq. (2)). The plug resistance is the minimum of inner frictional resistance, q_{in} or soil base resistance, $q_{b,soil}$ (see Fig. 1). The plug resistance is significantly 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.

$$q_b = q_{an} + q_{plug} \quad (2)$$

Where q_b is base resistance.

Various empirical approaches are currently used to evaluate shaft and base resistance of driven piles in sandy soils [1]. The vast number of design approaches has mainly been resulted due to the inadequacy of existing theoretical methods to predict the soil response [2]. While soil density influences bearing capacity of open-ended piles, interpretation of the influence of it is highly uncertain due to poor definition of soil properties along the pile length [3]. However, the cone penetration test for soil characterization provides reliable and repeatable information on vertical variability of the soil properties and therefore leads to improve the design reliability [4].

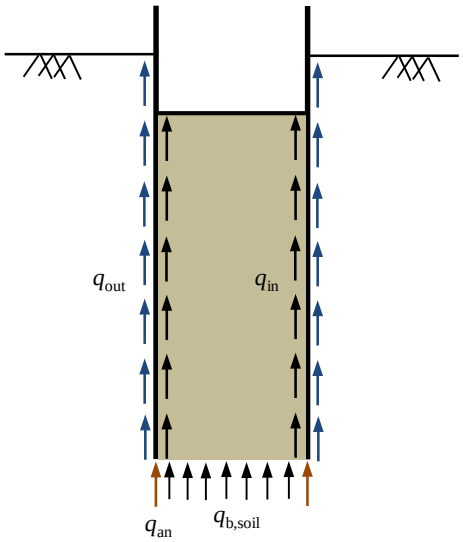


Fig. 1 The bearing capacity of an open-ended pile

The evaluation of the base resistance is not straightforward as the shaft resistance due to the effects of soil plugging. The effect of soil plugging on the base resistance is incorporated by different ways in many established design methods. In this paper, we discussed evaluation methods of the base resistance by several design methods including both CPT- and SPT-based design methods. Nowadays, CPT-based design methods are quite popular in many parts of the world although Japan still does not encourage cone penetration tests, mainly due to the inability of the cone to penetrate through relatively harder soils in Japan than many other countries, particularly in Europe. Three CPT-based design methods (i.e., ICP-05, UWA-05 and Fugro-05), one SPT-based method (i.e., PARI) and one earth pressure approach (i.e., API) are included in this study. The PARI method is widely used in Japan, particularly in offshore pile foundations such as in port and airport constructions.

Although load tests reduce the level of uncertainty for onshore applications, load tests are quite expensive in offshore applications. Therefore, the accuracy of bearing capacity of driven piles in offshore applications is relied heavily on the empirical design methods [5]. The CPT is considered as a model pile and has a long history of using for estimation of axial pile capacity [6]. However, there is considerable variations among the CPT-design methods used worldwide [7] since the controlling factors of the bearing capacity are influenced by more soil parameters than those affecting the CPT tip resistance [8].

While countries like Japan and South Korea prefer the use standard penetration tests, many countries in the world now prefer cone penetration tests. The database of the field piles with both CPT q_c and SPT-N profiles are very hard to be found, particularly in Japan, where the use of cone penetration test is quite rare. In the last decade, two field piles constructed in the Tokyo Bay construction project provide both SPT-N and CPT q_c profiles [9-11].

In this study, the base resistance of the two field piles was evaluated using the aforementioned design methods. The comparison of each method is important to select the best design method for open-ended piles penetrated in sandy soils. Each of the design methods has its own definitions for many parameters as explained in the following sections.

1.1 ICP-05 Method

ICP-05 design method is based on the cone penetration test (CPT) results [12]. It produces design formulae for both sandy and clayey soils. The base resistance of an unplugged open-ended pile driven in sandy soil is given in Eq. (3). The average cone resistance, $q_{c,avg}$ (see Eq. (3)) is determined taking the average of CPT q_c within ± 1.5D (D is pile outer diameter) from the pile tip as suggested by [13] (also known as the Dutch method). In this method, a fixed distance of 1.5D towards both directions from the pile tip is considered for the average cone resistance regardless of the variation in ground conditions along the depth. As indicated in Eq. (3), the ratio of q_b to the average q_c varies with the area ratio, which is influenced by pile outer and inner diameters.

$$q_b = A_r q_{c,avg} \quad (3)$$

Where q_b is base resistance, A_r is area ratio (see Eq. (4)) and $q_{c,avg}$ is average CPT resistance.

$$A_r = 1 - \left(\frac{d}{D}\right)^2 \quad (4)$$

Where d and D are inner and outer pile diameter respectively.

In the ICP-05 design method, an open-ended pile is considered plugged if the following conditions are satisfied. If any of the two conditions is not satisfied, then it is considered as an unplugged pile.

$$d < 0.02(D_r - 30) \text{ and } \frac{d}{D_{CPT}} < 0.083\frac{q_c}{p_a}$$

Where d is inner pile diameter (in meters), D_r is relative density (in percentage), D_{CPT} is diameter of CPT probe (in meters), q_c is CPT resistance and p_a is reference pressure (i.e., usually taken as the atmospheric pressure of 100 kPa).

The base resistance of a plugged open-ended pile is evaluated using Eq. (5). In Eq. (5), two lower limits are provided for a fully-plugged open-ended pile (i.e., the capacity of the unplugged pile by $A_r q_{c,avg}$ and the capacity predicted for the piles of D > 0.9 m by 0.15$q_{c,avg}$ [12]. Since the maximum value of the three is selected as the base resistance, Eqs. (3) and (5) simply indicate that a plugged open-ended pile does not produce a smaller base resistance than a similar unplugged open-ended pile.

$$q_b = q_{c,avg}\text{Max}\left(0.5 - 0.25\log\left(\frac{D}{D_{CPT}}\right), 0.15, A_r\right) \quad (5)$$

Where D_{CPT} is diameter of CPT probe.

1.2 UWA-05 Method

UWA-05 design method is also based on the cone penetration test. It was developed largely from the ICP method by incorporating several modifications [14]. Hence, it considered a larger database than the ICP and Fugro methods. This method, unlike other CPT-based design methods, introduces an effective area ratio, which combines the incremental filling ratio and annular area ratio of the pile [15-16]. This method proposes a single

equation for both closed- and open-ended piles as given in Eq. (6). The effective area ratio in Eq. (6) becomes the unity for closed-ended piles (i.e., A_{ef} = 1). Therefore, the base resistance of a closed-ended pile is simply given by 0.6 times the design cone penetration resistance (i.e., $0.6q_{c,avg}$).

$$q_b = q_{c,avg}(0.15 + 0.45A_{ef}) \quad (6)$$

Where A_{ef} is effective area ratio as given in Eq. (7).

$$A_{ef} = 1 - FFR\left(\frac{d}{D}\right)^2 \quad (7)$$

Where *FFR* is final filling ratio as given in Eq. (8).

$$FFR = \text{Min}\left[1, \left(\frac{d}{1.5}\right)^{0.2}\right] \quad (8)$$

Where *d* is inner pile diameter (in meters).

The FFR is the incremental filling ratio (IFR) defined for the final penetration equal to 20 pile diameters. The incremental filling ratio is defined as given in Eq. (9) [17-18]. When the measurement of IFR is not available (which is the usual case for the field piles), Eq. (8) is used to determine the FFR. The $q_b/q_{c,avg}$ ratio in Eq. (6) depends on the annular area and the degree of soil plugging over the final stages of pile penetration. This ratio varies from 0.15 for a thin-walled open-ended pile (i.e., 1 of *FFR*) to 0.60 for a fully-plugged open-ended pile (i.e., 0 of *FFR*) same as a closed-ended pile.

$$IFR = \frac{\Delta h}{\Delta H} \times 100(\%) \quad (9)$$

Where *IFR* is incremental filling ratio and Δh is the change of soil plug height for the penetration depth of ΔH.

The design cone penetration resistance, $q_{c,avg}$ is evaluated according to the Dutch method as given in Eq. (10) [19]. The CPT resistance in the zone A, $q_{c,A}$ (see Eq. (10) and Fig. 2) is the average of the envelope of minimum cone resistance recorded above the pile tip over 8*D* (*D* is pile outer diameter) distance. The CPT resistance in the zone B, $q_{c,B}$ is evaluated as given in Eq. (11).

$$q_{c,avg} = 0.5(q_{c,A} + q_{c,B}) \quad (10)$$

Where $q_{c,A}$ and $q_{c,B}$ are CPT resistance of zone A and B respectively (see Fig. 2).

$$q_{c,B} = 0.5(q_{c,avg,B} + q_{c,min,B}) \quad (11)$$

Where $q_{c,avg,B}$ is the average cone resistance recorded below the pile tip over 0.7 – 4*D* distance and $q_{c,min,B}$ is the minimum cone resistance recorded below the pile tip over the same distance of 0.7 – 4*D*.

The selection of the influence zone below the pile tip (i.e., from 0.7 to 4*D*) depends on variation of the cone penetration resistance. In case of significant variations in q_c, a distance of 4*D* is selected. However, in the UWA-05 design method, the pile diameter, *D* is used only for closed-ended piles while it is replaced by the effective pile diameter given in Eq. (12) for open-ended piles.

$$D_{ef} = DA_{ef}^{0.5} \quad (12)$$

Where D_{ef} is effective pile diameter.

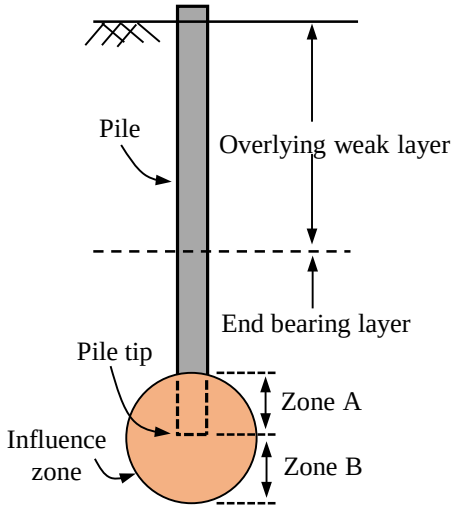


Fig. 2 A schematic diagram of the influence zone of CPT q_c resistance

1.3 Fugro-05 Method

The Fugro design method is also based on the cone penetration test. It also proposes a single equation for both closed- and open-ended piles as given in Eq. (13) [20]. The area ratio in Eq. (13) becomes the unity for closed-ended piles (i.e., A_r = 1).

$$q_b = 8.5q_{c,avg}\left(\frac{p_a}{q_{c,avg}}\right)^{0.5} A_r^{0.25} \quad (13)$$

Where p_a is reference pressure (i.e., 100 kPa).

The $q_{c,avg}$ is evaluated taking the average of CPT q_c within ± 1.5*D* (*D* is pile outer diameter) from the pile tip same as in the ICP method. Therefore, both ICP-05 and Fugro-05 design methods consider the same influence zone for the evaluation of the base capacity.

1.4 API Method

The API design method is based on the earth pressure. The base resistance is evaluated using Eq. (14) [21]. The dimensionless bearing capacity factor in Eq. (14) depends on the soil type and soil density. The value of N_q can be read from a table given in [21]. The table also gives the limiting base

resistances for different ground conditions (see Table 1).

$$q_b = \sigma_v' N_q \quad (14)$$

Where σ_v' is effective overburden pressure at the pile tip and N_q is dimensionless bearing capacity factor (see Table 1).

Table 1 Design parameters for cohesionless siliceous soil (modified from [21])

Density	Soil description	Soil-pile friction angle (degree)	N_q	Limiting unit end bearing resistance (MPa)
Very Loose	Sand	15	8	1.9
Loose	Sand-Silt			
Medium	Silt			
Loose	Sand	20	12	2.9
Medium	Sand-Silt			
Dense	Silt			
Medium	Sand	25	20	4.8
Dense	Sand-Silt			
Dense	Sand	30	40	9.6
Very Dense	Sand-Silt			
Dense	Gravel	35	50	12.0
Very Dense	Sand			

1.5 PARI Method

PARI design method is based on the SPT-*N* value [22]. Since Japan does not prefer CPT-based design methods, this method is quite popular in offshore foundation designs in Japan. In the PARI method, the base resistance is evaluated using Eq. (15). In this method, the degree of soil plugging is incorporated in the base resistance by a dimensionless parameter, α (see Eq. 15).

$$q_b = 300\alpha N^* \quad (15)$$

Where α is a dimensionless parameter and *N** is the design SPT-*N* value evaluated as given in Eq. (16).

$$N^* = 0.5(N_1 + N_2) \quad (16)$$

Where N_1 is SPT-*N* value at the pile tip (≤ 50) and N_2 is the average SPT-*N* value recorded above the pile tip over 4*D* (*D* is pile outer diameter) distance (≤ 50).

It should be noted that the maximum SPT-*N* value for both N_1 and N_2 (and hence *N** as well) is limited to 50 regardless of the actual measurements. Unlike the CPT-based design methods, the PARI method does not take account the ground condition below the pile tip when evaluating the design SPT-*N* value.

Table 2 briefly summaries the influence zones applied for CPT- and SPT-based design methods. It clearly indicates that the influence zone defined in each design method is different to each other except between the ICP and Fugro methods, which use the same method. As given in Table 2, the UWA-05 design method consider the ground variations for a longer depth compared to the other methods.

Table 2 The influence zone for the average CPT-q_c and SPT-*N* values

Design method	Above pile tip	Below pile tip
ICP	1.5*D*	1.5*D*
UWA	8*D*	0.7-4*D*
Fugro	1.5*D*	1.5*D*
PARI	4*D*	-

Note: *D* is pile outer diameter

2. RESULTS AND DISCUSSIONS

The details of the two field piles used in this study can be found in [9, 11]. Fig. 3 shows the ground profile at the T4 and T5 piles. T4 and T5 piles are embedded into sandy gravel and dense sand layers respectively. The dry density, ρ_t of clayey and sandy soils are taken as 1400 – 1550 and 1700 -1750 kg/m^3 respectively. The ρ_t of sandy gravel and dense sand are taken as 2208 and 1850 kg/m^3 respectively [9]. The water level is at 7 m from the pile head. The base resistance of the two piles have been evaluated for 73.5 and 86 m depths for T4 and T5 piles respectively by the load tests. CPT q_c and SPT-*N* profiles at the site are shown in Figs. 4a and 4b respectively.

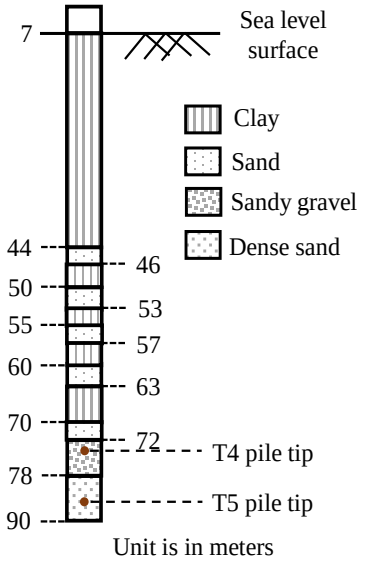


Fig. 3 The simplified ground profile at the site (modified from [9])

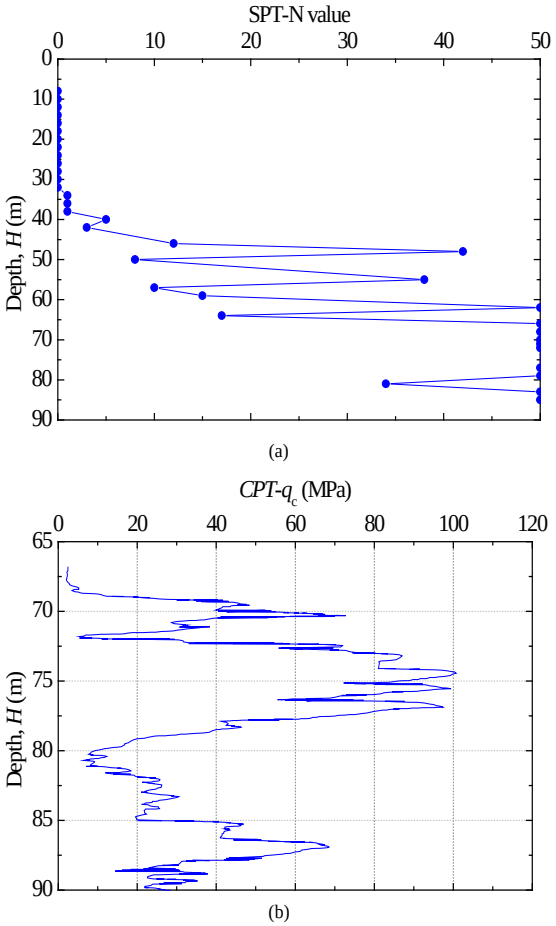


Fig. 4 (a) SPT-*N* profile (modified from [23]) and (b) an enlarged CPT q_c profile at the pile tip (modified from [24])

CPT resistance in the zone A and B, $q_{c,A}$ and $_{qc,B}$ respectively (see Fig. 2) for ICP-05 and Fugro-05 methods are 50.14 and 89.57 MPa respectively for T4 pile. The design CPT q_c value (i.e., $q_{c,avg}$) for both ICP-05 and Fugro-05 methods then becomes 69.86 MPa for T4 pile. $q_{c,A}$ and $q_{c,B}$ for UWA-05 method are 27.66 and 80.42 MPa respectively for T4 pile. As seen here, the UWA-05 method produces different CPT q_c values for the two zones above and below the pile tip unlike ICP-05 or Fugro-05 methods. The design $q_{c,avg}$ then becomes 54.04 MPa, which is slightly smaller than the ICP-05 and Fugro-05 methods produced. The $q_{c,avg}$ for T5 pile is summarised in Table 3 along with the results of T4 pile. $q_{c,B}$ for UWA-05 method (see Eq. (11)) was evaluated for 4*D* (*D* is pile outer diameter) distance below the pile tip as the variation of CPT q_c was non-uniform.

The value of α (see Eq. (15)) was taken as 0.302 using a non-linear relationship proposed for the data available in [22] as shown in Fig. 5. Figure 5 also indicates that a linear relationship would produce a larger value of α (i.e., 0.396) which then should produce a larger base resistance (see Eq. (15)). The SPT-*N* values of N_1 and N_2 were found to be 50 and 45 respectively (see Eq. (16)). The measured N_1 was higher than 50. However, since the PARI method has a limiting value of 50, it was selected as 50. Then, the design SPT-*N* value (i.e., *N**) for the PARI method becomes 47.

Table 3 The results of $q_{c,avg}$ from the CPT-based design methods

Design method	$q_{c,A}$ (MPa)		$q_{c,B}$ (MPa)		$q_{c,avg}$ (MPa)	
	T4 pile	T5 pile	T4 pile	T5 pile	T4 pile	T5 pile
ICP	50.14	31.16	89.57	50.75	69.86	40.95
UWA	27.66	20.90	80.42	34.78	54.04	27.84
Fugro	50.14	31.16	89.57	50.75	69.86	40.95

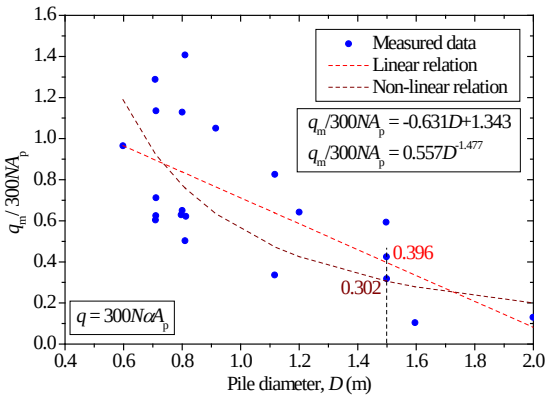


Fig. 5 The results of α parameter (modified from [22])

Figures 6a and 6b show the base resistance of T4 and T5 piles respectively. The results clearly suggest that API and Fugro-05 methods overestimate the base resistance for both piles. In fact, the API method gives 12.84 and 14.97 MPa for the base resistance of T4 and T5 piles respectively by Eq. (14), which are much higher than the corresponding measured values (i.e., 8.88 and 6.37 MPa respectively). However, since the API method assigns a limiting value (see Table 1), the limiting values are used in Figs. 6a and 6b. In both T4 and T5 piles, N_q was assumed to be 40. However, given the soil condition, the use of even 50 of N_q would be possible, which then would have overestimated the measured values even by a larger margin. This design method is quite tricky compared to the other methods since it does not take variations within a soil type. All other design methods included in this paper incorporate the average behaviour of the ground at the pile tip, either as the average CPT q_c or SPT-*N* value.

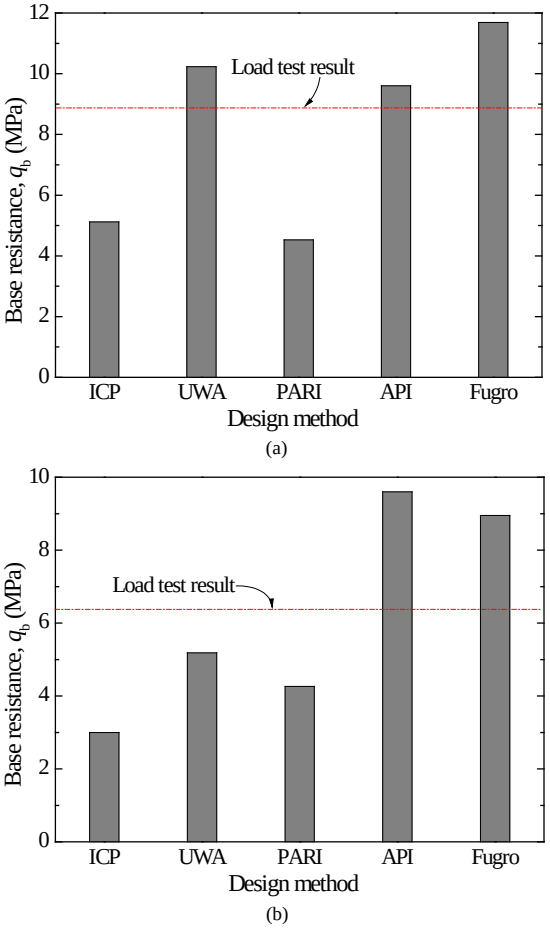


Fig. 6 Base resistance of (a) T4 and (b) T5 pile respectively

In contrast, ICP and PARI methods underestimate the base resistance in both piles (see Figs. 6a and 6b). As given in Table 4, the PARI produces slightly lesser variations from the measured base resistance compared to the ICP-05 method. Therefore, based on a conservative approach, we can recommend the ICP and PARI methods for the evaluation of base resistance of unplugged open-ended piles. However, they underestimate the base resistance by a big margin as given in Table 4. The PARI method limits the design SPT-*N* value to 50 regardless of its measured value (see Eq. (16)). Therefore, it is worth to study how this limit SPT-*N* value influences the base resistance. Also, it was understood that the PARI method does not incorporate the ground conditions below the pile tip like all the CPT-based methods do. Given the ground condition below the pile tip is stiffer than the above it (in both piles, see Fig. 4b), a design formula incorporating the ground conditions below the pile tip will produce a higher base resistance, which then would reduce the gap between the measured and designed values.

Table 4 The difference of design base resistance from the measured value

Design method	T4 pile ($q_{b,m}$ = 8.88 MPa)		T5 pile ($q_{b,m}$ = 6.37 MPa)	
	Base resistance, q_b (MPa)	Difference from the actual value (%)	Base resistance, q_b (MPa)	Difference from the actual value (%)
ICP	5.12	-42	3.00	-53
UWA	10.23	+15	5.18	-19
PARI	4.53	-49	4.26	-33
API	9.60	+08	9.60	+51
Fugro	11.69	+32	8.95	+41

Note: + indicates overestimation, - indicates underestimation and $q_{b,m}$ is the measured base resistance

Among the design methods discussed in this paper, the UWA-05 method produces the nearest values to the measured base resistance although it overestimates the base resistance for one pile by a small margin (see Fig. 6a and Table 4). Therefore, based on a rational approach, we can recommend the UWA design method. Only the UWA method incorporates the incremental filling ratio (as a function of final filling ratio) into the design equation. The degree of soil plugging is described by the incremental filling ratio to a greater degree. Therefore, the UWA method incorporates the degree of soil plugging in the base resistance. Interestingly, the UWA-05 also considers different ground depths above and below the pile tip in evaluating the design CPT q_c value.

As aforementioned, both the ICP-05 and Fugro-05 methods assign the same criterial for the design CPT q_c value (see Table 2). Interestingly, they underestimate and overestimate the base resistance respectively for both piles. Therefore, we can also understand that not only the evaluation method of the design CPT q_c but also the other parameters contribute to the difference among the design methods.

3. CONCLUSSIONS

The base resistance of two field piles constructed in Tokyo bay project was evaluated by five different design methods. The study includes both CPT- and SPT-based design methods in addition to soil pressure-based one widely practiced in the US. The following conclusions were drawn from the study.

The closest results to the measured base resistance was achieved by the UWA-05 design method, which is the only method incorporates the incremental filling ratio (or degree of soil plugging) explicitly in the design equation.

The ICP-05 and PARI (a method practiced popularly in Japan) underestimate the base resistance, approximately by similar margins. The use of a limiting SPT-*N* value (rather than the

measured value) in the PARI method produces a smaller base resistance, which results in a larger gap between the designed and measured values. Also, incorporating the ground conditions below the pile tip like in the CPT-based design methods may reduce the difference. Therefore, further study on the PARI method is recommended.

API design method overestimates the base resistance even after assigning the smaller limiting values provided. The dimensionless parameter (i.e., N_q) suggested for the soil type and density needs a further study as it could result a base resistance deviated much from the actual value as observed in this study.

Fugro-05 method gives the least matched results to the measured base resistance. Given other CPT-based design methods give better results, we do not encourage the use of Fugro-05 method for open-ended piles.

It should be noted that the results in this paper were produced only from two field piles. Therefore, we recommend that the modifications to the existing design methods should come after a large number of field piles are studied. This study though provides the basic of a comparison of the SPT- and CPT-based design methods, which could be used for further studies.

4. ACKNOWLEDGEMENTS

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