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Comparison of SPT-based design methods for vertical capacity of piles installed by Rotary Cutting Press-in

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ABSTRACT: The applicability of the Press-in Method to hard grounds has been significantly improved by the development of Rotary Cutting Press-in (RCP), where vertical and rotational forces are simultaneously applied to a pile with base cutting teeth. Although RCP piles are usually used for retaining walls, there have been some cases where they are used for foundations. Several SPT-based design methods for RCP piles have been prepared so far. Some of these are based on existing design codes in Japan for piles installed by other piling methods, which are intended for specific construction fields (roads and railways). This paper overviews these existing SPT-based design methods for RCP piles, and proposes another method by making adjustments on the existing design method for the field of buildings in Japan, based on the results of five static load tests on RCP piles.

1 INTRODUCTION

The applicability of the Press-in Method to hard grounds has been significantly improved by the recent development of installation techniques such as Press-in with Augering and Rotary Cutting Press-in (RCP, which installs piles by applying vertical and rotational forces onto a pile with base cutting teeth). Although piles installed by these installation techniques are usually used for retaining walls, there have been some cases where RCP piles are used for foundations. Several design methods for RCP piles have been prepared so far (IPA, 2014, Suzuki *et al*., 2019; JSCE, 2020), based on some existing design codes in Japan for piles installed by other piling methods. These methods are intended for specific construction fields (roads and railways), to fit for the conventional style in Japan where different design codes based on different design concepts are adopted in different construction fields. There is another research (Ishihara *et al*., 2020) providing a method of estimating the base capacity of RCP piles either from CPT or SPT results, which was obtained by introducing a method to estimate the plugging condition (*IFR*, Incremental Filling Ratio) into the framework of CPT-based UWA-05 design method (Lehane *et al*., 2005).

This paper firstly overviews some of the above-mentioned SPT-based design methods for RCP piles. After that, another method will be proposed by making adjustments on the existing code for the field of buildings in Japan, based on the results of five static load tests on RCP piles.

2 EXISTING DESIGN METHODS FOR VERTICAL CAPACITY OF RCP PILES

2.1 *IPA (2014)*

There had been no design methods for the vertical capacity of RCP piles until the method of IPA (2014) was prepared, by adjusting the SPT-based method for driven piles (JRA, 2012) based on three load test results including that of Hirata *et al*. (2009).

According to JRA (2012), the base capacity (Q_{bf}) of a driven pile is expressed as:

$$Q_{\mathrm{bf}} = q_{\mathrm{bf}} \times A_{\mathrm{b,closed}} \tag{1}$$

$$q_{\mathrm{bf}} = 300 \times \min\left(\frac{z_{\mathrm{bs}}}{5D_{\mathrm{o}}}, 1\right) \times \min(N_{\mathrm{D0}}, 40)\ [kPa] \tag{2}$$

where q_{bf} is the unit base capacity, $A_{\mathrm{b,closed}}$ is the cross-sectional area of a fully plugged (closed-ended) pile, z_{bs} is the embedment length into a bearing stratum (defined as the layer with SPT N not smaller than 30 in JRA (2012)), D_{o} is the outer diameter of the pile and N_{D0} is the "bearing stratum N value" determined by

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the SPT N values in the depth range from the pile base to 4 D_o above the pile base. IPA (2014) recommended the value of z_{bs} for RCP piles to be 1 D_o, aiming for assuring the efficiency of piling work by avoiding excessive time for installing a pile into a hard layer while securing a certain level of the vertical performance of the pile. As a result, in IPA (2014), the unit base capacity is obtained by:

$$q_{bf} = \min(60 \times N_{D1}, 2400) \text{ [kpa]} \quad (3)$$

Note that the averaging method for N is different from that in JRA (2012), with N_{D1} being the N value averaged from the pile base to 1 D_o above the pile base. It is also noted that the bearing stratum is defined in IPA (2014) as the layer with SPT N not being smaller than 40.

On the other hand, in IPA (2014), the shaft capacity (Q_{sf}) is expressed as:

$$Q_{sf} = \int (q_{sf} \times \pi D_o) dz \quad (4)$$

$$q_{sf} = \begin{cases} \min(2 \times N,\ 100) & [kPa] \text{ (for sand)} \\ \min(8 \times N,\ 100) & [kPa] \text{ (for clay)} \end{cases} \quad (5)$$

where q_{sf} is the unit shaft capacity.

The ratio of design load to the ultimate capacity ($A_{D/f}$) is prescribed in IPA (2014) as:

$$\frac{Q_D}{Q_f} \equiv A_{D/f} = \frac{1}{3} \quad (6)$$

$$Q_f = Q_{bf} + Q_{sf} \quad (7)$$

where Q_D is the design load and Q_f is the ultimate capacity.

2.2 *JSCE (2020)*

The method of JSCE (2020) was prepared in response to the revision of JRA (2012) into JRA (2017). In JRA (2017), the concept of reducing q_{bf} for smaller z_{bs} (Eq. (2)) was removed, and as a result, the following simpler expression has newly been provided for piles having z_{bs} values equal to or greater than 2 D_o.

$$q_{bf} = \begin{cases} \min(130 \times N_{D2},\ 6500) & [kPa] \text{ (for sand)} \\ \min(90 \times N_{D2},\ 4500) & [kPa] \text{ (for clay)} \end{cases} \quad (8)$$

where N_{D2} is the arithmetic average of SPT N value from the pile base to 3 D_o below the pile base.

In JSCE (2020), JRA (2017) was adjusted based on five load test results introduced later in Section 3.2, and Q_{bf} and Q_{sf} are estimated by:

$$Q_{bf} = q_{bf} \times A_{b,closed} \quad (= \text{Eq.}(1)) \quad (9)$$

$$q_{bf} = 4500 \text{ [kPa] (for gravelorsand, } N_{D2} \geq 40) \quad (10)$$

$$Q_{sf} = \int (q_{sf} \times \pi D_o) dz \quad (= \text{Eq.}(4)) \quad (11)$$

$$q_{sf} = \begin{cases} \min(5 \times N,\ 50) & [kPa] \text{ (for sand)} \\ \min(6 \times N,\ 50) & [kPa] \text{ (for clay)} \end{cases} \quad (12)$$

The main point in the revision of JRA (2012) into JRA (2017) was the introduction of the partial factor design method and the limit state design method, which has been reflected in a more sophisticated (subdivided) expression of the ratio of design load to the ultimate capacity ($A_{D/f}$) as follows:

$$A_{D/f} = A_{D/y} \times A_{y/f} \quad (13)$$

$$A_{D/y} = \xi_1 \phi_r \lambda_f \quad (14)$$

where $A_{D/y}$ is the ratio of design load (Q_D) to yield load (Q_y, the first-limit-resistance), $A_{y/f}$ is the ratio of yield load (Q_D) to ultimate capacity (Q_f), ξ is the parameter called "investigation and analysis factor", Φ_y is the parameter called "resistance factor" and λ_f is the parameter to consider the effect of the pile type (e.g. end-supported pile or friction pile). JSCE (2020) provides each value of these parameters, but this paper will only quote the values of $A_{D/y}$ and $A_{y/f}$ for simplicity, later in Table 3.

2.3 *Suzuki et Al. (2019)*

Suzuki *et al.* (2019) proposed a design method for RCP piles, by analyzing the five load test results introduced later in Section 3.2 based on statistical processing and reliability analysis, as instructed in RTRI (2012) and RTRI (2018). Their method is expressed as:

$$Q_{bf} = q_{bf} \times A_{b,closed} \quad (= \text{Eq.}(1)) \quad (15)$$

$$q_{bf} = \begin{cases} \min(60 \times N_{D3},\ 3500) & \text{[kPa] (for sand)} \\ \min(60 \times N_{D3},\ 7500) & \text{[kPa] (for gravel)} \end{cases} \quad (16)$$

$$Q_{sf} = \int (q_{sf} \times \pi D_o) \text{dz} \quad (= \text{Eq.}(4)) \quad (17)$$

$$q_{sf} = \min(2 \times N, 40) \quad \text{[kPa] for sand, clay} \quad (18)$$

$$\frac{Q_{\mathrm{D}}}{Q_{\mathrm{f}}} \equiv A_{\mathrm{D/f}} \tag{19}$$

$$Q_{\mathrm{f}}=Q_{\mathrm{bf}}+Q_{\mathrm{sf}} \quad (= \text{Eq.}(7)) \tag{20}$$

where N_{D3} is the smallest N value in the depth range from 1 D_o above to 3 D_o below the pile base. $A_{D/f}$ can be obtained by a chart shown in Figure 1.

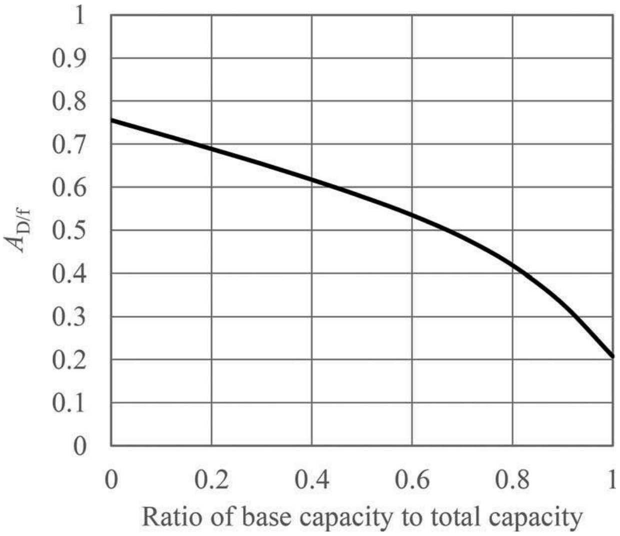


Figure 1. Ratio of design load to the ultimate capacity (after Suzuki et al., 2019).

3 PROPOSAL OF A DESIGN METHOD FOR RCP PILES IN THE FIELD OF BUISLINGS

3.1 *Framework of AIJ (2019) design method*

The latest design method for piles in the field of buildings in Japan is provided in AIJ (2019). Q_{bf} and Q_{sf} of driven piles are expressed as:

$$Q_{\mathrm{bf}} = \eta \times q_{\mathrm{bf}} \times A_{\mathrm{b,closed}} \tag{21}$$

$$\eta = \begin{cases} \min\left(0.16\times\frac{z_{\mathrm{bs}}}{d_{\mathrm{i}}}, 0.8\right) & (\text{for open} - \text{ ended}, \frac{z_{\mathrm{bs}}}{d_{\mathrm{i}}} \geq 2) \\ 1 & (\text{for closed} - \text{ended}) \end{cases} \tag{22}$$

$$q_{\mathrm{bf}} = \begin{cases} \min(300\times N_{\mathrm{D4}}, 18000) & [\mathrm{kPa}]\ (\text{for sand}) \\ \min(6 \times c, 18000) & [\mathrm{kPa}]\ (\text{for clay}) \end{cases} \tag{23}$$

$$Q_{\mathrm{sf}} = \int (q_{\mathrm{sf}} \times \pi D_{\mathrm{o}}) dz \quad (= \text{Eq.}(4)) \tag{24}$$

$$q_{\mathrm{sf}} = \begin{cases} \min(2 \times N, 100) & [\mathrm{kPa}]\ (\text{for sand}) \\ \min(0.8 \times c, 100) & [\mathrm{kPa}]\ (\text{for clay}) \end{cases} \tag{25}$$

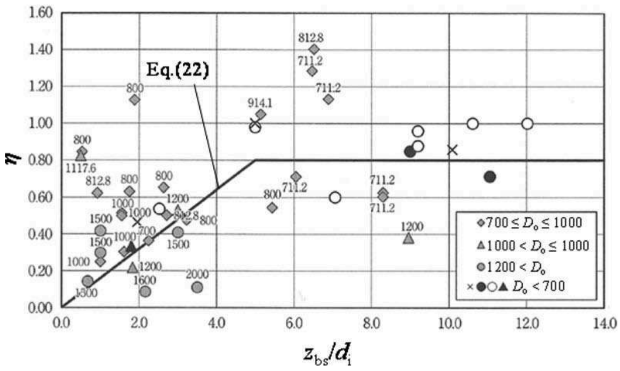


Figure 2. Plug efficiency (after AIJ (2019)).

Here, in general, the base capacity will increase as the open-ended pile becomes more plugged, and the pile will become more plugged as the embedment into the bearing stratum becomes longer. In AIJ (2019), these relationships are considered by introducing the plug efficiency η (Eq. (22), Figure 2), d_i is the inner diameter of the pile, N_{D4} is the SPT N value averaged from 4 D_o above to 1 D_o below the pile base, and c is the cohesion of the soil. The bearing stratum is defined as the layer having the SPT N values greater than 50. The way of considering the plugging condition is similar to that in JRA (2012), which can be confirmed by comparing q_{bf} obtained by Eq. (2) and $\eta \times q_{bf}$ obtained by Eqs. (22) and (23).

AIJ (2019) is a limit-state design method. Piles in their ultimate limit state, damage limit state and serviceability limit state are supposed to exhibit Q_f, two-thirds of Q_f and one-third of Q_f respectively, where Q_f is the ultimate capacity.

3.2 *Load test database*

In this paper, information of five static load tests on RCP piles were collected, as summarized in Table 1. Tests I2006, T2007 and F2008 were conducted by Hirata *et al.* (2009) and outlined in IPA (2014). Detailed information on A2016 and N2017 can be found in Ishihara *et al.* (2016) and Okada *et al.* (2021) respectively. Site profiles and the press-in conditions for these tests are shown in Figure 3 and Table 2 respectively. Load test conditions were basically in compliance with JGS standard (JGS, 2002), except for the shorter period from the end of installation to the start of load test in A2016 and the existence of adjacent piles within the horizontal distance of 3 D_o from the center of the test pile in I2006, T2007 and F2008.

I2006 was conducted at an initial stage of the development of this piling method. The pile accidentally experienced strong plugging during its installation, and it was extracted fully (with its inner soil column being stuck to the pile) and installed again (after removing the plugged soil). In A2016, the pile was installed by RCP down to 2m BGL and by Standard Press-in (press-in without any installation assistance) in deeper than 2m.

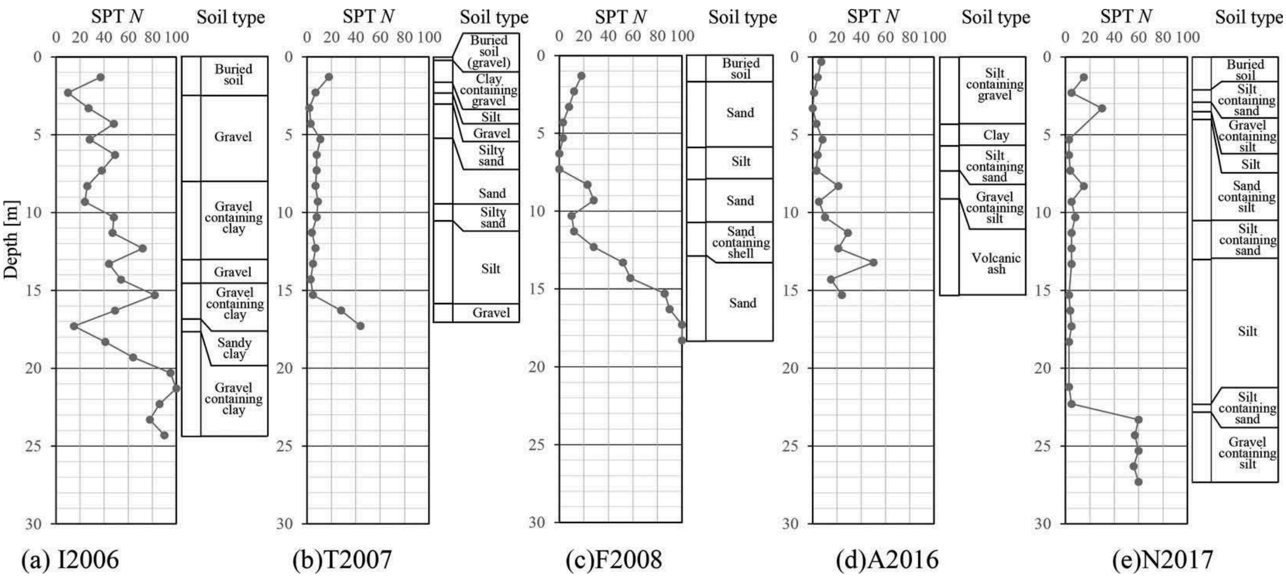


Figure 3. Site profiles.

Table 1. Load test databases.

(a) Test conditions

Test name	Pile Diameter D_o [mm]	Pile Thick-ness t [mm]	Embed-ment depth z [m]	Embed-ment length z_{bs} [m]	Curing period t_c [day]
I2006	800	16	19.65	0.9	18
T2007	800	16	17.5	0	16
F2008	1000	12	15	1.7	15
A2016	800	12	4.7	0	1
N2017	1000	12	24	0.8	57

(b) Test results

Test name	Total capacity Q_f [kN]	Base capacity Q_{bf} [kN]	Shaft capacity Q_{sf} [kN]
I2006	4168	2548	1620
T2007	4060	2368	1692
F2008	6363	3576	2787
A2016	578	363	215
N2017	5000	3102	1898

Table 2. Press-in conditions.

Test name	Jacking force [kN]	Flowrate of water injection [L/min]	Number of base teeth
I2006	500~900	30	4→8
T2007	400	10~ 30	4
F2008	500	20~ 30	5
A2016	300	0	4
N2017	300	15	6

3.3 *Adjusting AIJ (2019) based on load test results*

In this sub-section, the AIJ (2019) design method will be adjusted for RCP piles based on the load test results introduced in the previous sub-section.

For base capacity, η was back-analyzed by assuming that Eqs. (21) and (23) directly apply to RCP piles. It can be found in Figure 4 that the same expression as Eq. (22) provides the lower limit for the load test databases. However, the correlation between the plots of load test results and the estimation line given by Eq. (23) is very weak. One major reason was thought to be the effect of averaging of SPT

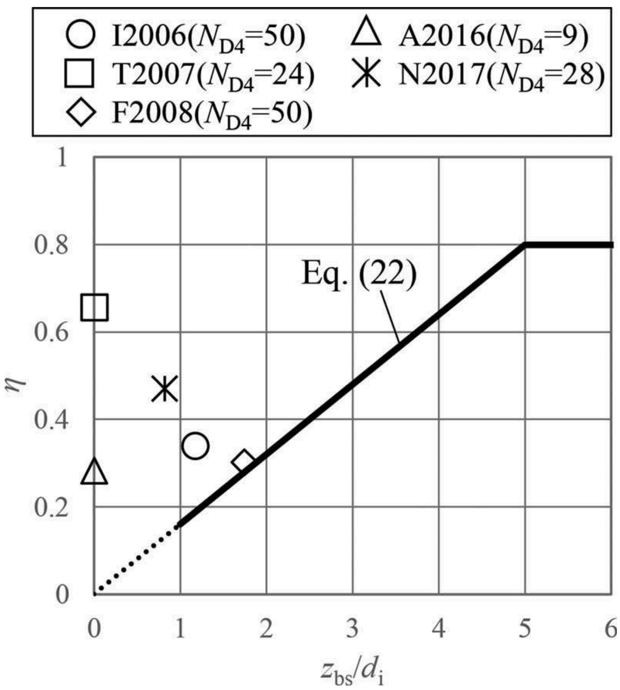


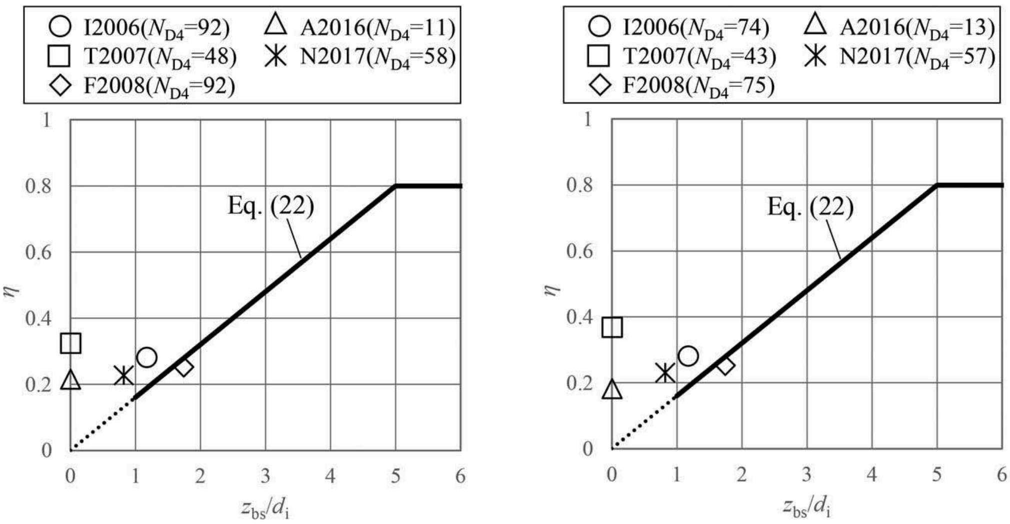
Figure 4. Comparison of η back-analyzed by load test data and estimated by Eq.(22).

N (averaged from 4 D_o above to 1 D_o below the pile base in Figure 4). Figure 5 shows the results of the same analyses with different averaging methods (averaged from 0 to 3 D_o below the pile base in Figure 5 (a) and averaged from 1 D_o above to 1 D_o below the pile base in Figure 5(b)). Better correlations between the load test results and the estimation lines can be found in Figure 5 compared with those in Figure 4. Figure 6 shows the comparison of measured and estimated base capacities. It can be confirmed that all the estimated values are conservative, and better matches can be obtained when the SPT N values are averaged either from 0 to 3 D_o below the pile base or from 1 D_o above to 1 D_o below the pile base.

For shaft capacity, values of constants in Eq. (25) were back-analyzed based on the q_{sf} values obtained by the strain gauge readings in the load tests and the SPT N values averaged over the corresponding depth ranges. For sands, as shown in Figure 7(a), q_{sf} = 3.5N with its upper limit (q_{sf}^{UL}) being 100kPa provides a reasonable threshold, with the excess ratio (ratio of load test data plots exceeding the estimation line) being greater than 75% as instructed in AIJ (2019). For clays, as shown in Figure 7(b), the threshold of q_{sf} = 6N gives the excess ratio of 75%, while the q_{sf}^{UL} value is difficult to be judged. Figure 8 is the comparison of the measured and estimated Q_{sf}, with estimation provided based on different q_{sf}^{UL} values. It can be confirmed that q_{sf}^{UL} = 100kPa (as adopted in Eq. (25)) provides a slightly conservative results than the average trends in the load test results, with slight overestimation for two of the four load test results (excluding I2006 due to the irregularity experienced in its installation as previously explained).

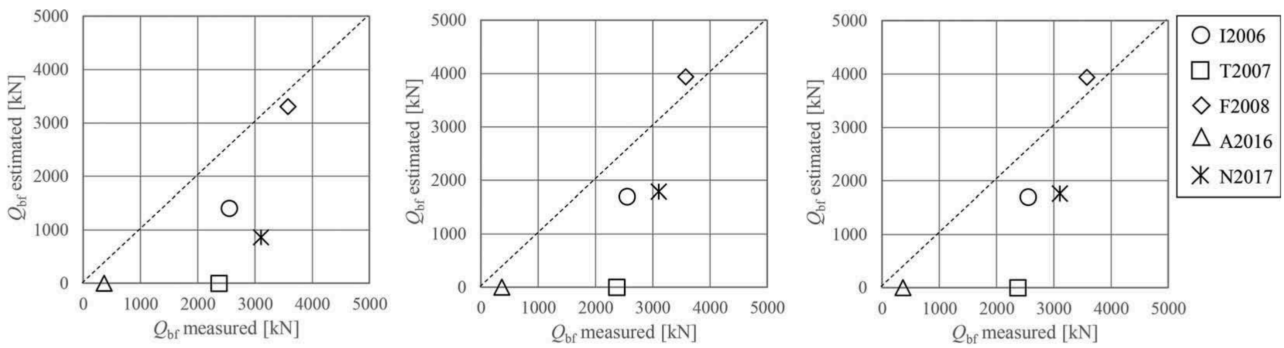
3.4 *Comparing the SPT-based design methods*

The SPT-based design methods reviewed in Section 2 and proposed in Section 3.3 are summarized in Table 3. Here, the ultimate limit state, damage limit state and serviceability limit state in AIJ (2019) were interpreted by the authors as corresponding to the states where a pile shows its ultimate capacity, yield load and design load respectively. The subdivided expression of $A_{D/y}$ in JSCE (2020) was simplified in this table to enable an easier comparison. It should also be noted



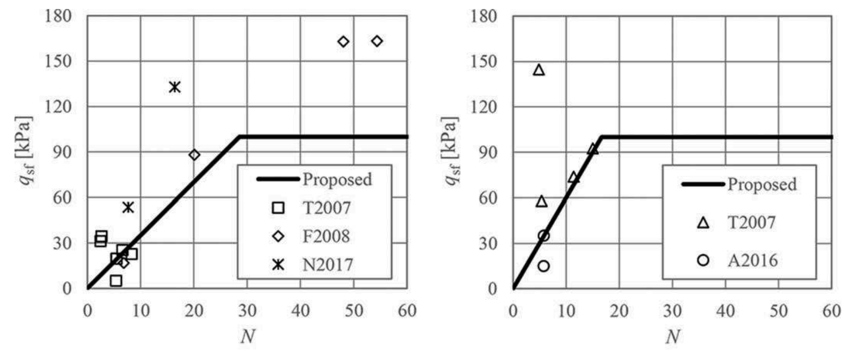
(a) From 0 to 3 D_o below the base (b) From 1 D_o above to 1 D_o below the base

Figure 5. Effect of different averaging methods on back-analyzed η.



(a) From 4 D_o above to 1 D_o below the base (b) From 0 to 3 D_o below the base (c) From 1 D_o above to 1 D_o below the base

Figure 6. Comparison of Q_{bf} obtained in load test and estimated by the proposed method with different averaging methods.



(a) Sand (b) Clay

Figure 7. Correlation between unit shaft capacity and SPT N values.

Table 3. Comparison of SPT-based design methods for RCP piles in Japan.

	Code		IPA (2014)	JSCE (2020)	Suzuki et al. (2019)	Proposed
	Instalation method		RCP	RCP	RCP	RCP
(1)	Ratio of design load to ultimate capacity, $A_{D/f}$(=$A_{D/y}$×$A_{y/f}$)		1/3	0.32	Figure 1	-
(2)	Ratio of design load to yield load, $A_{D/y}$			0.72		-
(3)	Ratio of design load to ultimate capacity, $A_{y/f}$			0.45		-
(4)	q_{bf}	clay				
		sand	$60N_b \leqq 2400$	4500 ($N_b \geqq 40$)	$60N_b \leqq 3500$	$300N_b \leqq 18000$
		gravel	$60N_b \leqq 2400$	4500 ($N_b \geqq 40$)	$60N_b \leqq 7500$	
(5)	η		1	1	1	Eq.(22)
(6)	q_{sf}	clay	$8N \leqq 100$	$6N \leqq 50$	$2N \leqq 40$	$6N \leqq 100$
		sand	$2N \leqq 100$	$5N \leqq 50$	$2N \leqq 40$	$3.5N \leqq 100$
(7)	Definition of bearing stratum		$N \geqq 40$	$N \geqq 40$	$N \geqq 30$	$N \geqq 50$
	Reqired z_{bs} value		$1D_o$	$1D_o$	$1D_o$	$1D_o$
	Range of N considered for q_{bf}	Bearing stratum				
		Embedded depth	above $1D_o$		above $1D_o$	above $1D_o$
		N_b	average	below $3D_o$ average	below $3D_o$ minimum	belw $1D_o$ average
(8)	Target performance of estimation		Lower limit of load test database	Average of load test database	Lower limit of load test database	base : Excess ratio 50% shaft : Excess ratio 75%

that N_{D4} in the proposed method was obtained by averaging SPT N values from 1 D_o above to 1 D_o below the pile base, to reflect the discussion in the previous section.

Figure 9 shows the comparison of Q_{bf}, Q_{sf} and Q_f obtained in the load tests and those estimated by different design methods. Q_{bf} was estimated reasonably, except for the significant underestimations by IPA (2014) (as intended in this design method as explained in Section 2.1). Q_{bf} remained almost constant with the value of z_{bs} in IPA (2014), Suzuki *et al.* (2019) and JSCE (2020), while it increased significantly with z_{bs} in the proposed method due to the effect of η. This can lead to a significant overestimation if the pile is embedded into the bearing stratum deeper than the z_{bs} values of the load test databases in this paper (at most about 2 D_o). For Q_{sf}, the result in I2006 was overestimated by all the methods, due to the irregular extraction to remove the plugged soil. In the other tests, significant (about half) underestimations were found in Suzuki *et al.* (2019) (as intended in this design method as explained in Section 2.3), while a slight overestimating trend was found in IPA (2014). For Q_f, good agreement with the load test results were found in the proposed method and JSCE (2020), while conservative estimation results were yielded by the other two methods.

Figure 10 shows the comparison of design loads (Q_D) obtained by IPA (2014), Suzuki *et al.* (2019) and JSCE (2020). It can be seen that similar Q_D

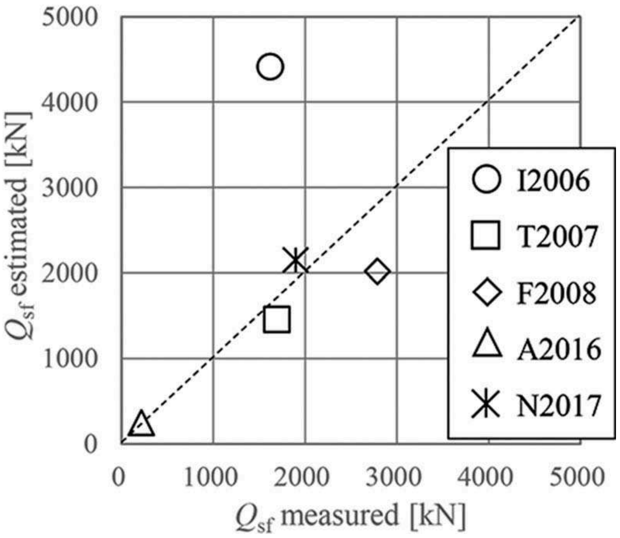


Figure 8. Comparison of measured and estimated $Q_{s.}$

values were obtained by Suzuki *et al*. (2019) and JSCE (2020) despite their difference in estimating Q_f values, and these values were greater than what was obtained by IPA (2014). It is necessary to obtain a value of $A_{D/f}$ for the proposed method in the future.

4 CONCLUSIONS

Existing SPT-based design methods for RCP piles were reviewed, and another method was proposed by making adjustments on the existing design method for the field of buildings in Japan, based on the results of four static load tests on RCP piles. Comparing the estimation results and the field test results, it was confirmed that the ultimate capacity obtained by each code was different from each other but the design load obtained by each code was more

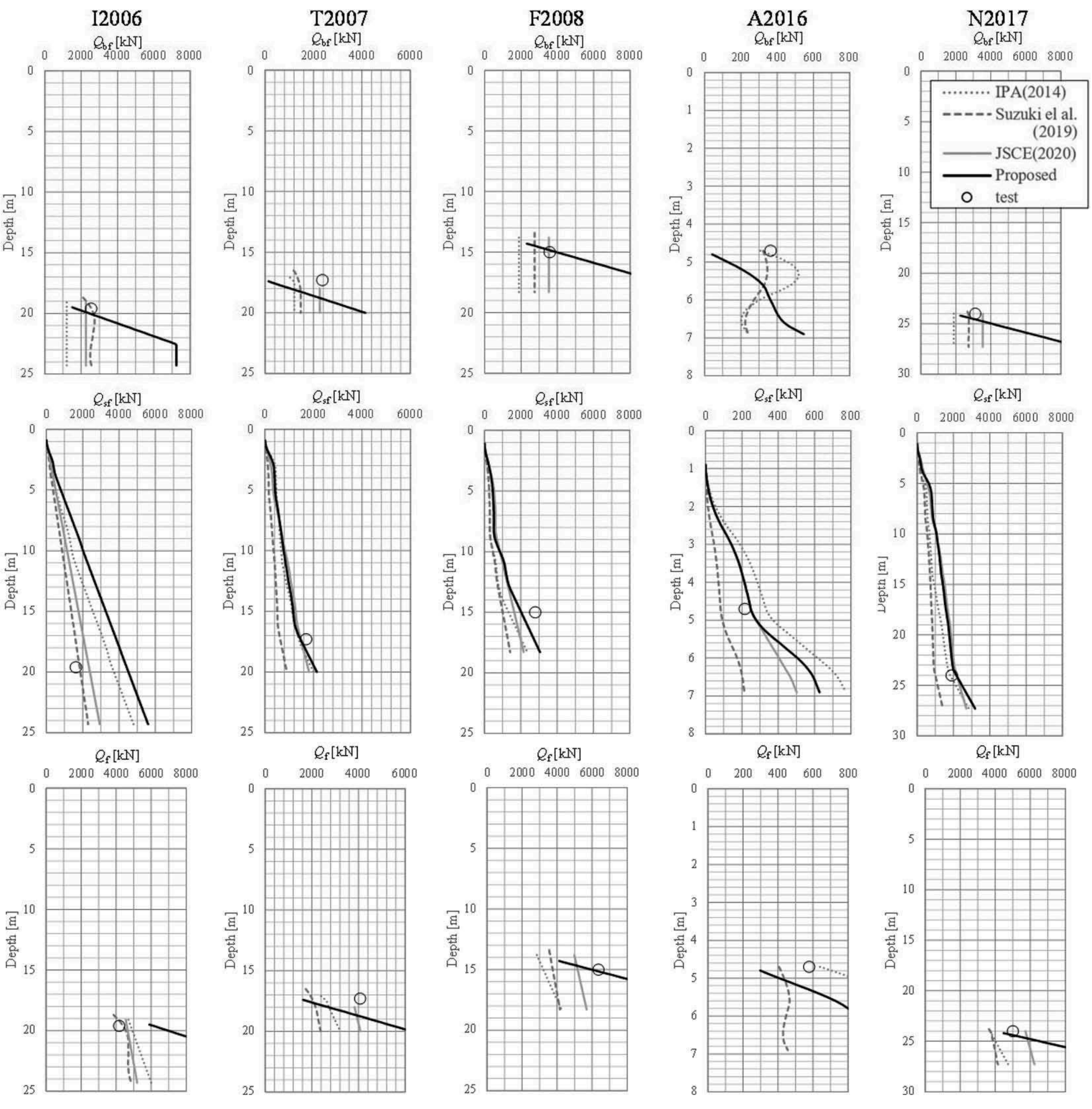


Figure 9. Comparison of Q_{bf}, Q_{sf} and Q_f obtained in load tests and estimated by SPT-based design methods.

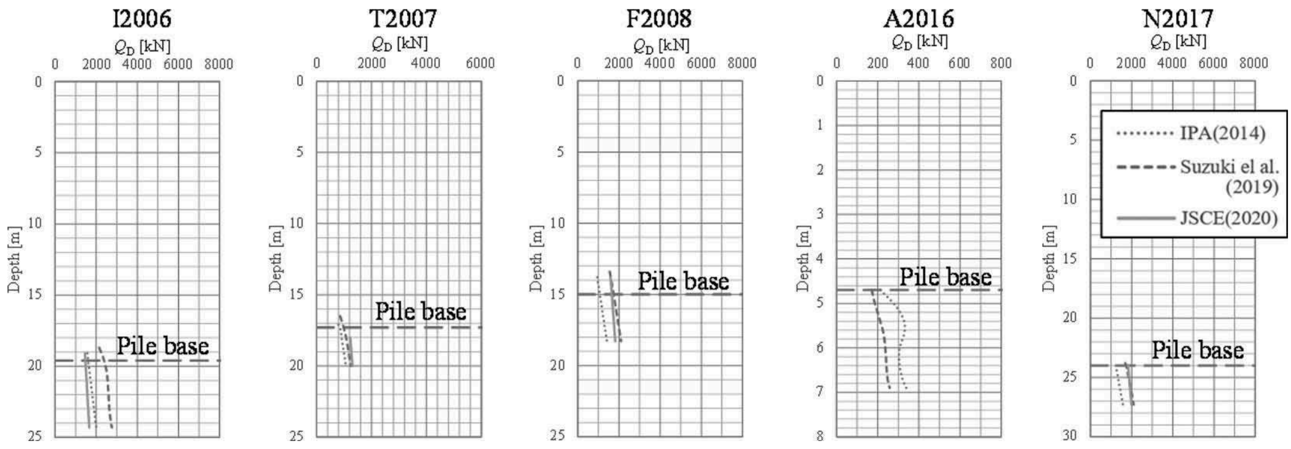


Figure 10. Comparison of Q_D estimated by SPT-based design methods.

similar to each other. It was also confirmed that the base capacity estimated by the proposed method sharply increased in the bearing stratum due to the consideration of the plugging condition, which could lead to significant overestimation for RCP piles installed into the bearing stratum by greater than about 2 times its outer diameter. It was recognized that the ratio of the design load to the ultimate capacity obtained by the proposed method has to be clarified in the future.

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