A case study on bearing capacities of driven steel pipe piles from load tests and empirical formulas based on SPT and CPT

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Abstract

In Japan, Standard Penetration Test (SPT) *N*-value is widely used for estimating bearing capacities of foundation piles with empirical equations. SPT *N*-values are obtained at depths of 1 m intervals at a location, resulting in insufficient information about soil stratification. In contrast, three parameters such as cone tip resistance, sleeve friction and pore water pressure are measured in electric Cone Penetration Test (CPT) at depths of 20 mm intervals. Hence, demands on CPT are gradually increasing in the field of pile foundation engineering in Japan. In this research, Static Load Test (SLT) and Rapid Load Tests (RLTs) on an open-ended steel pipe pile (SPP) were carried out at the Jibanshikenjo test yard in Sashima, Ibaraki Prefecture, Japan. The test pile had an outer diameter of 318.5 mm, a wall thickness of 6.6 mm and an embedment length of 11.0 m. SPT and CPTs were carried out. The ground at the test site is alternate layers of sand, clay and silt having SPT *N*-values less than 35. In this paper, shaft resistance f_s and tip resistance q_b directly obtained from the SLT are compared with those estimated from the RLTs and various empirical equations using SPT *N*-value and CPT tip resistance q_t.

Keywords: *bearing capacity; steel pipe pile; static load test; rapid load test; SPT; CPT*

1. INTRODUCTION

Jibanshikenjo Co. Ltd. carried out comparative tests of Static Load Test (SLT) and Rapid Load Rest (RLT) on driven steel pipe piles (SPPs) at the Sashima test yard. Standard Penetration Test (SPT) and Cone Penetration Test (CPT) were carried out prior to the comparative tests.

In this study, the maximum tip resistance q_b and the maximum shaft resistance f_s estimated from empirical formulas of various standards are compared with the results from SLT and RLTs.

2. PILE LOAD TESTS

2.1 Site conditions

Figure 1 shows the results of soil investigations (SPT-*N* value, cone resistance corrected for pore pressure at filter q_t), embedment of the instrumented test pile.

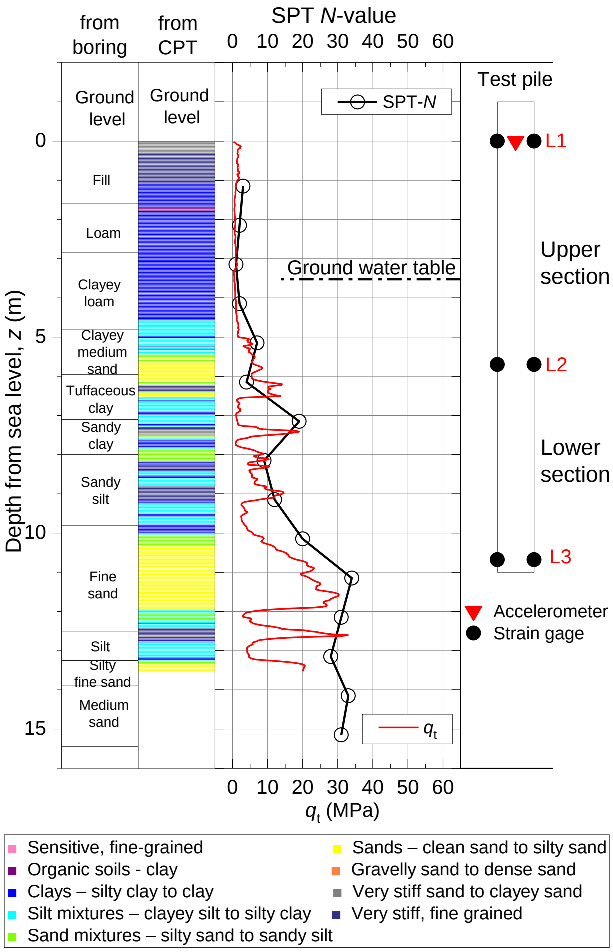

Figure 115. Profiles of soil layers, SPT N-values and CPT q_t, together with instrumented test pile

2.2 Test pile

Table 1 shows the specifications of the test steel pipe pile (SPP). Channel steels were welded on the test SPP for protecting strain gages and accelerometers.

The test pile was instrumented with strain gages at 3 levels as shown in Figure 1. Accelerometers were set at the only top level (L1).

Table 1. Specifications of test pile

Item	Value	
	Original	with protection
Pile length, L (m)	11.8	
Embedment length, L_d (m)	11.0	
Outer diameter, D_o (mm)	318.5	
Inner diameter, D_i (mm)	305.3	
Wall thickness, t_w (mm)	6.6	
Cross-sectional area, A (m^2)	0.00651	0.00926
Circumferential length, U (m)	1.00	1.20
Young's modulus, E (GPa)	205	
Density, ρ (ton/m^3)	7.81	
Bar wave velocity, c (m/s)	5123	
Mass, m (ton)	0.610	0.819

N.B. The steel protection was welded outside the pile shaft, and the interpretation of the measured signals was carried out using the properties of the test pile with the protection.

2.3 Results of pile load tests

RLTs were carried out 8 days after the step loading SLT on the same pile. In RLTs, hammer mass m_h = 3.5 ton was used and 8 blows (RLTs) were applied to the pile with increasing drop height *h* from 0.03 to 0.83 m [1].

Figure 2 shows the pile head (at L1) load-displacement relations and the pile tip (at L3) load-displacement relations from SLT and RLTs. In this study, q_b and f_s from SLT and RLTs were estimated at the maximum loads, respectively.

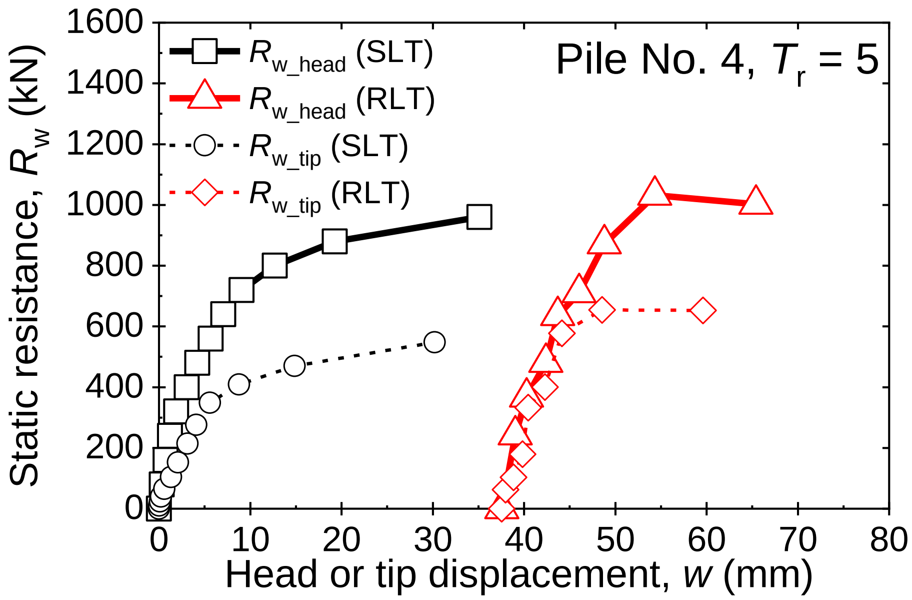

Figure 2. Static load-displacement relations from SLT and RLTs

3. DESIGN EQUATIONS SPECIFIED IN VARIOUS CODES

Tables 2 and 3 show the empirical equations for q_b and f_s of open-ended driven piles, based on Unified CPT design method for sand [2] and clay [3].

Table 2. Estimation of maximum tip resistance q_b and maximum shaft resistance f_s based on Unified CPT method for sand [2]

$q_b = 0.4q_c\left[\exp(-2\times PLR)+4t/D_o\right]\le 0.4q_c$
$f_s = \tau_f = 0.39\left(\sigma'_{rc} + \Delta\sigma'_{rd}\right)$
$\sigma'_{rc} = \left(q_c/44\right)A_{re}^{0.3}\left[\text{Max}\left[1,\ h/D_o\right]\right]^{-0.4}$
$\Delta\sigma'_{rd} = \left(q_c/10\right)\left(q_c/\sigma'_v\right)^{-0.33}\left(d_{CPT}/D_o\right)$
$A_{re} = 1 - PLR\left(D_i/D_o\right)^2$
$PLR = \tanh\left[0.3\left(D_i/d_{CPT}\right)^{0.5}\right]$; $d_{CPT} = 35.7$ mm
q_c = cone tip resistance, t = pile wall thickness, h = height of given point on shaft above the pile base, σ_v' = in-situ vertical effective stress, d_{CPT} = diameter of cone

Table 3. Estimation of maximum tip resistance q_b and maximum shaft resistance f_s based on Unified CPT method for clay [3]

$q_b = \left(0.2 + 0.6 A_{re}\right) q_t$
$f_s = \tau_f = 0.07 F_{st}\ q_t\ \mathrm{Max}\left[1, \left(h/D^*\right)\right]^{-0.25}$
$D^* = \left({D_o}^2 - {D_i}^2\right)^{0.5}$ for an open-ended pile
$F_{st} = 1$ for organic clay, silty clay to clay, clayey silt to silty clay
$F_{st} = 0.5 \pm 0.2$ for sensitive, fine-grained clays
q_t = cone resistance corrected for pore pressure at filter

Table 4 shows the empirical equations for q_b and f_s of driven piles specified in various Japanese codes.

Table 4. Estimation of maximum tip resistance q_b and maximum shaft resistance f_s based on Japanese codes [4, 5, 6, 7]

Code	Tip / Shaft (kPa)	Soil type		Note
		Sand	Clay	
Road [4]	Tip, q_b	$130N$ ($\leqq 6500$)	$90N$ ($\leqq 4500$)	
	Shaft, f_s	$5N$ ($\leqq 100$)	$6N$ or $1c$ ($\leqq 70$)	c = cohesion (undrained shear strength)
Port [5]	Tip, q_b	$300\eta N$ ($\leqq 15000$)	$6c$	$N = (N_1+N_2)/2$, N_1 = N-value of the ground at pile tip, N_2 = mean N-value in the range of $4D_o$ above the pile tip, η = plugging efficiency
	Shaft, f_s	$2N$ ($\leqq 100$)	$1c$ ($\leqq 100$)	
Archi. [6]	Tip, q_b	$300\eta N$ ($\leqq 18000$)	$6c$ ($\leqq 18000$)	$\eta = 0.16\left(L_B/D_i\right)$ for $2 \leq \left(L_B/D_i\right) \leq 5$, $\eta = 0.8$ for $5 < \left(L_B/D_i\right)$, L_B = embedment length into bearing stratum, D_i = inner pile diameter
	Shaft, f_s	$2N$ ($\leqq 100$)	$0.8c$ ($\leqq 100$)	
Railway [7]	Tip, q_b	$210N$ ($\leqq 10000$)	6.3c or $75N$ ($\leqq 20000$)	for CPP, N = mean N-value in the range of $3D_o$ below the pile tip
		$175N$ ($\leqq 8000$)	$55N$ or $5.5c$ ($\leqq 16000$)	for OPP w/ $D_o \leqq 0.8$ m and $l/D_o > 5$, N = N-value of the ground at the pile tip, l = equivalent embedment length into bearing stratum, $l = [5\ D_o\ (N_1+N_2)/2]/N$, N_1 = N-value at $5D_o$ above the pile tip, N_2 = N-value of the ground at pile tip, D_o = outer pile diameter
		$35(l/D_o)N$ ($\leqq 8000$)	$11(l/D_o)N$ or $1.1(l/D_o)c$ ($\leqq 16000$)	for OPP w/ $D_o \leqq 0.8$ m and $l/D_o \leqq 5$, N = N-value of the ground at the pile tip
		$(140/D_o)N$ ($\leqq 8000$)	$(44/D_o)N$ or $(4.4/D_o)c$ ($\leqq 16000$)	for OPP w/ $D_o > 0.8$ m and $l/D_o > 5$, N = N-value of the ground at the pile tip
		$(28/D_o)(l/D_o)N$ ($\leqq 8000$)	$(8.8/D_o)(l/D_o)N$ or $(0.88/D_o)(l/D_o)c$	for OPP w/ $D_o > 0.8$ m and $l/D_o \leqq 5$, N = N-value of the ground at the pile tip

			(≦16000)	
	Shaft, f_s	$3N$+30 (≦150)	$6N$ or $0.4c$ (≦120)	for CPP
		$3N$ (≦120)	$6N$ or $0.4c$ (≦120)	for OPP

CPP: Close-ended Pipe Pile, OPP: Open-ended Pipe Pile

4. COMPARISON OF PILE RESISTANCES FROM SLT WITH THOSE FROM RLT AND VARIOUS CODES

Figure 3 shows the distributions with depth of shaft resistance f_s from the SLT, RLT and various design codes.

Notice that when the empirical equation using only c is specified in the Japanese codes, c = $6.25N$ (kPa) was assumed. F_{st} was set as 0.3 in the Unified CPT method (Table 3).

In Figure 3, the dotted lines are the shaft resistance f_s estimated from the various design codes. The solid lines indicate the average values of f_s for the upper pile section and lower pile section which are for the comparison with the SLT result. The thick solid lines are the measured f_s in SLT and RLTs.

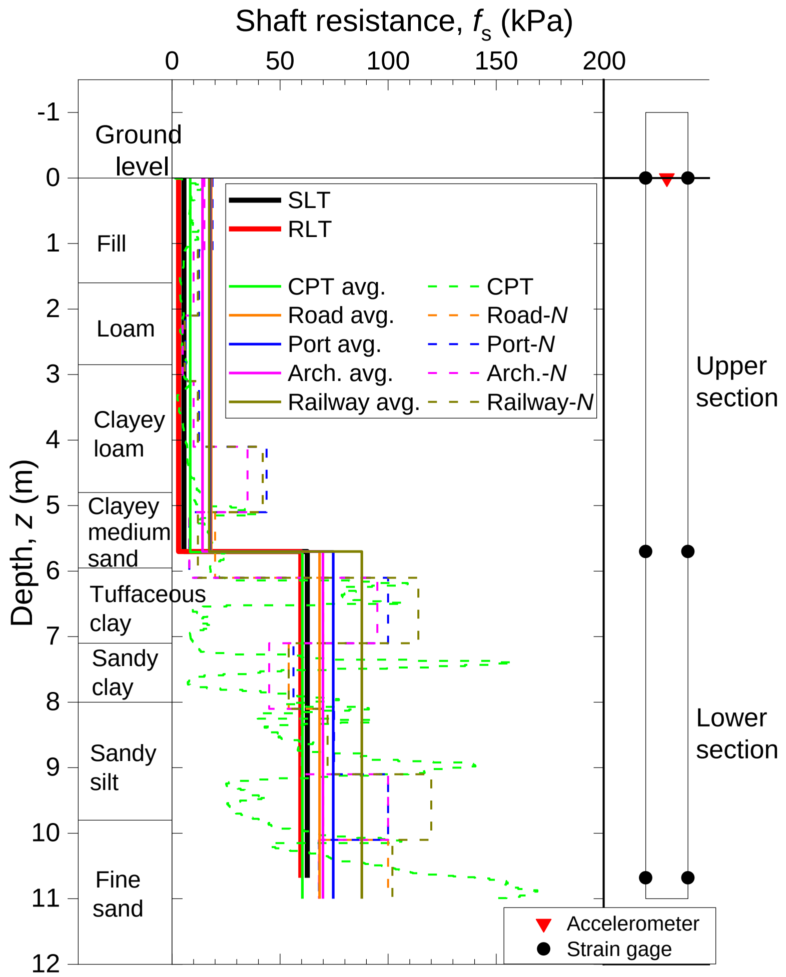

Figure 3. Distributions of shaft resistance f_s from SLT, RLT and design codes

Figure 4 shows the comparison of average shaft resistance f_s of two pile sections from SLT, RLT and the design codes. Although there is no big difference between Japanese codes, Japanese codes overestimate the SLT result. On the other hand, the shaft resistance f_s from CPT and RLT are almost equal to the SLT result.

Figure 5 shows the comparison of maximum shaft resistance Q_s and maximum tip resistance Q_b from SLT, RLT and the design codes. The trend of Q_s is similar to that described in Figure 3. There is a wide variation in Q_b from the design codes including CPT method. The plugging efficiency η = 1 in Port code and Road code while η = 0.52 in Architectural code for this particular test pile condition.

Q_b from RLT is the most reasonable estimation for the SLT result.

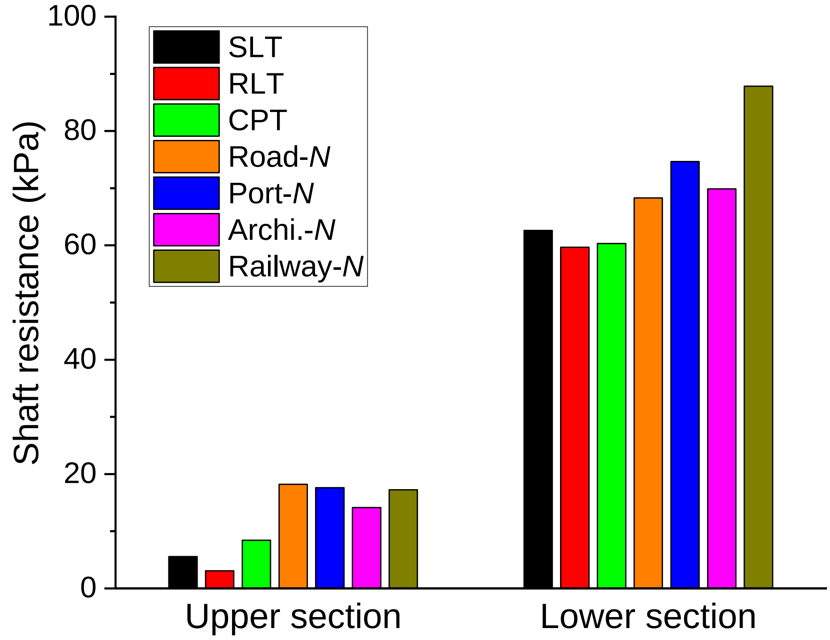

Figure 4. Comparison of average shaft resistance f_s of two pile sections from SLT, RLT and design codes

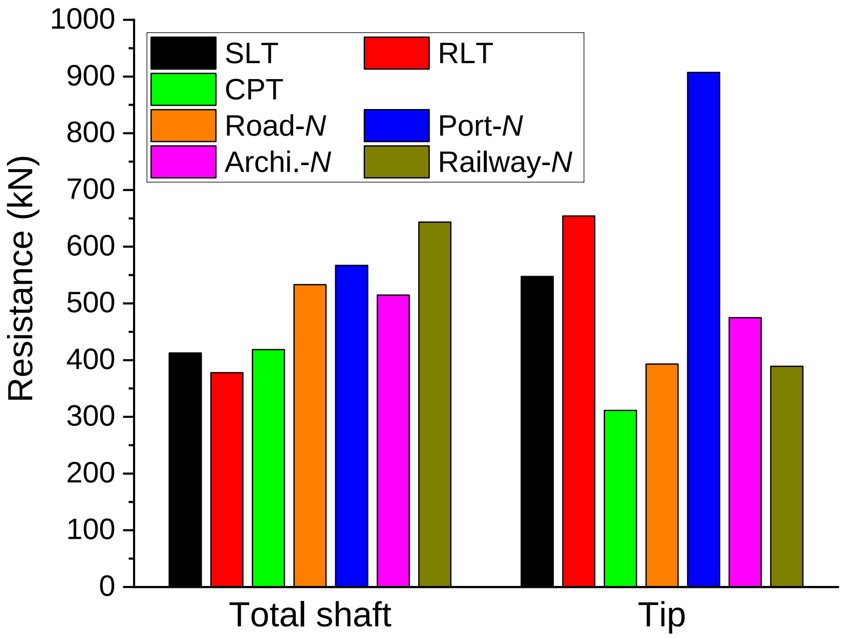

Figure 5. Comparison of maximum shaft resistance Q_s and maximum tip resistance Q_b from SLT, RLT and design codes

Figure 6 shows the comparison of pile axial force distributions at ultimate states from SLT, RLT and the design codes. The pile axial force distributions from the design codes were obtained by stacking the maximum shaft resistance of each measurement interval (0.02 m in CPT, 1 m in SPT), starting from the maximum tip resistance Q_b. Changes in pile axial force from various design codes including CPT show similar trends. Since the *N*-value was used in Japanese design codes, the changes of the axial force occur at 1 m intervals, while the pile axial force from CPT method shows more detail pile axial force changing at 0.02 m intervals. Pile axial force distribution from RLT corresponds very well to the SLT result.

Estimation of pile axial force distribution is beneficial for the preliminary design of pile body.

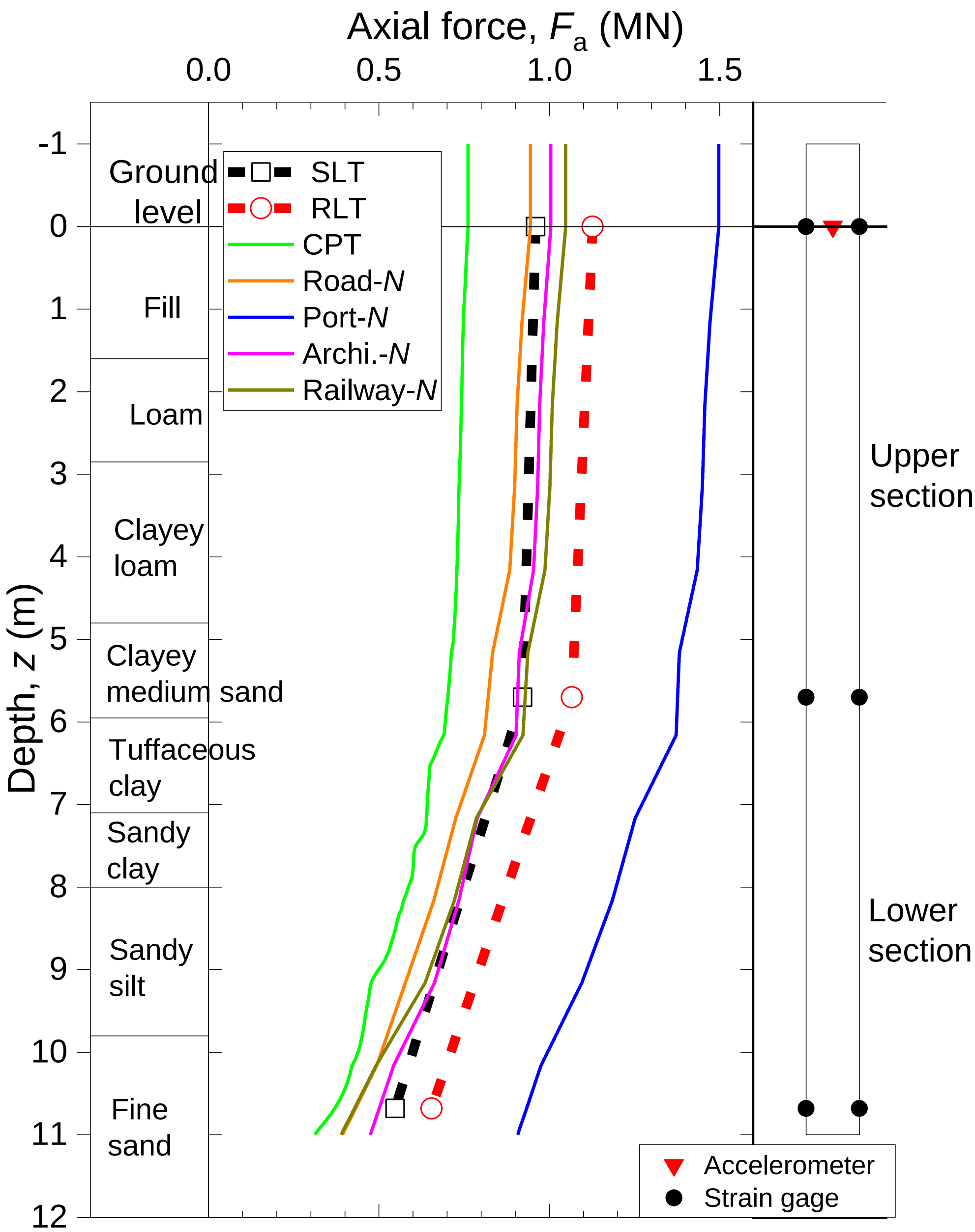

Figure 6. Comparison of pile axial force distributions at ultimate states from SLT, RLT and design codes

CONCLUSION

Comparative tests of SLT and RLT on a driven steel pipe pile were carried out in this study. SPT and CPT were carried out prior to the comparative tests. The maximum tip resistance q_b and the maximum shaft resistance f_s estimated from empirical formulas of various codes were compared with the results from SLT and RLTs.

There was no signification difference of shaft resistance f_s between SLT, RLT and the results from various design codes. On the other hand, there was a large variation in tip resistance from the various design codes. The results of RLT were the most comparable to the SLT results.

CPT is capable of catching detail variation of soil layers. To promote the application of CPT in pile design, it is necessary to accumulate a database of estimation of pile capacity using CPT through more comparative studies in Japan.

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