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A comparative study of European and Japanese pile design codes based on a test site data

Une étude comparative des codes de conception de pieux européens et japonais basée sur les données d'un site d'essai

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ABSTRACT: Pile Static Load Test (SLT) and Rapid Load Test (RLT) results at the Jibanshikenjo test site in Sashima were compared to the empirical pile resistances estimated based on SPT and CPT measurements proposed by different European (EC7 National Annexes) and Japanese codes. RLT requires an interpretation, however, it is quick to perform and for this case it was in close agreement with SLT. The empirical pile resistance calculations from SPT and CPT vary in terms of methodology, gave different results and no consistent trend, especially for the tip resistance. Concerning the shaft resistance BS code for shaft resistance from SPT and Unified CPT, AFNOR and DIN codes from CPT gave good results. SLT and RLT must be considered more accurate, while the empirical methods should always consider local experience and preferably be compared to SLT or RLT results.

RÉSUMÉ: Les résultats des tests de charge statique et des tests de charge rapide sur le site d'essai de Jibanshikenjo à Sashima ont été comparés aux résistances empiriques des pieux estimées sur la base des mesures SPT et CPT proposées par différents codes européens (annexes nationales EC7) et japonais. RLT nécessite une interprétation, cependant, elle est rapide à réaliser et pour ce cas elle a été en étroit accord avec SLT. Les calculs empiriques de résistance des pieux de SPT et CPT varient en termes de méthodologie, ont donné des résultats différents et aucune tendance cohérente, en particulier pour la résistance aux pointes. Concernant la résistance à l'arbre BS pour la résistance à l'arbre du SPT et du CPT Unifié, l'AFNOR et le DIN du CPT ont donné de bons résultats. SLT et RLT doivent être considérés comme plus précis, tandis que les méthodes empiriques doivent toujours tenir compte de l'expérience locale et être de préférence comparées aux résultats SLT ou RLT.

Keywords: Pile resistance; design codes; representative value; empirical methods; Rapid Load Test.

1 GENERAL

The ultimate limit state (ULS) bearing capacity check of a single pile includes the calculation of the Ultimate Pile Load (UPL) representative value (R_{rep}), which corresponds to the pile bearing resistance failure (according to EN 1997-1:2004) or to the failure of the ground surrounding the piles (according to the upcoming 2nd generation EN 1997-3). In most cases, the bearing capacity calculation is based on static load tests, or on dynamic impact tests, or on ground tests results (e.g. EN 1997-1:2004) and these three alternatives result in different computational models, i.e. methods of calculation.

The static load test provides a direct estimation of the in situ total bearing resistance (R_c) or separately base (R_b) and shaft (R_s) resistances (EN 1997-1:2004). The dynamic impact test provides R_c, R_b and R_s after an interpretation and according to EN 1997-1:2004 "the validity of the result shall have been demonstrated by previous evidence of acceptable performance in static load tests on the same pile type of similar length and cross-section and in similar ground conditions".

Regarding methods to be incorporated based on ground tests the calculation results "shall have been established from pile load tests and from comparable experience" EN 1997-1: 2004. Ground test results may be either laboratory or in-situ tests. In Europe each country may propose a different calculation methodology, which is influenced by the local experience, for instance the DIN 1054, AFNOR NF P 94-262 and BS 8004 National Annexes (NAs) for EN 1997-1. For instance, the BS 8004, adopts the α-method if laboratory determined undrained shear strength (s_u) is available, or the β-method if drained shear strength (Mohr – Coulomb effective cohesion c' and effective angle of shearing resistance φ') is available. Notably, in Japan a variance of methods are prescribed in different Japanese Codes adopted by different authorities for their applications (Architectural Institute, Road Association, Ports and Harbours Bureau and Railway TRI). Concerning the use of in situ results all codes propose totally different methodologies.

The calculation of the UPL design value (R_d) differs on the way the design codes apply the factors of safety: a) Material Factor Approach (MFA), in which partial factors of safety are applied to the material strength constants or b) the Resistance Factor Approach (RFA), in which overall factors of safety are applied to the representative UPL.

This work performs a comparative analysis of the EC7 DIN, EC7 AFNOR, EC7 BS and four Japanese Codes with regards to in situ tests results carried out at the Jibanshikenjo test yard in Sashima Japan (Lin et al., 2023b).

2 ULTIMATE PILE LOAD

A general definition of the Ultimate Pile Load (UPL) representative value ($R_{c;rep}$) is presented in to Equation (1). The design value ($R_{c;d}$) depends whether the MFA or RFA approaches are adopted, or Equations (2) and (3) respectively. Equation (3) directly relates to Equation (1) by the overall factor of safety on the resistance. The EN 1997 signs have been adopted, while $X_d = X_{rep} / \gamma_M$ and $F_d = \gamma_F F_{rep}$ correspond to the design values of strength and loads respectively.

$$R_{c;rep} = R\left(F_{rep}, X_{rep}\right) \quad (1)$$

$$R_{c;d} = R\left(\gamma_F F_{rep}, X_{rep}/\gamma_M\right) \quad (2)$$

$$R_{c;d} = R_{c;rep}/\gamma_R = R_{c;rep}/\gamma_t \quad (3)$$

If bearing capacity is further analysed into the base (R_b) and the shaft (R_s) resistances, then:

$$R_{c;d} = R_{b;rep}/\gamma_b + R_{s;rep}/\gamma_s \quad (4)$$

The selection of MFA (Equation (2)) or RFA (Equation (3)) relates closely on the methodolody applied to estimate the single pile bearing capacity:

- Static Load Test (SLT) or Dynamic Impact Test: If it determines $R_{c;rep}$ applies RFA. If it determines $R_{b;rep}$ and $R_{s;rep}$ apply MFA or RFA (Equations (4) and (3) respectively).
- Ground Tests (GT): $R_{b;rep}$ and $R_{s;rep}$ are determined (Equations (5) and (6)). Empirical correlations are applied to laboratory results (soil strength constants) or in situ results (CPT, SPT), to calculate the representative base bearing capacity ($q_{b;rep}$) and shaft unit bearing capacity ($q_{s;rep}$, or $q_{s;i;rep}$ for ith layers). Either MFA or RFA (Equastions (4) and (3) respectively) can be applied.

$$R_{b;rep} = A_b q_{b;rep} \quad (5)$$

$$R_{s;rep} = \sum_{i=1}^{n} A_{s;i} q_{s;i;rep} \quad (6)$$

The MFA and RFA for pile $R_{c;d}$ calculation will give similar results for calculations from GT because the computational models are practically linear functions of the soil strength (c_u or c' and $\tan\varphi'$) or the in situ measurements (corrected cone resistance q_t, or blow counts N_{SPT}). This is in strong contrast with the shallow foundation case under drained conditions (e.g. Kovaiou & Belokas, 2023), where the bearing capacity equation is non-linear function of $\tan\varphi'$. Next, the European and Japanese methodologies for R_{rep} calculation of steel pipes are compared based on SLT (Static Load Test), RLT (Rapid Load Test) and in situ GT (SPT and CPT) results.

3 CALCULATION METHODS

DIN 1054 applies model factors $\eta_b < 1$ and $\eta_s < 1$ on Eqs. (5) and (6), i.e. $R_{b;rep} = \eta_b A_b\ q_{b;rep}$ and $R_{s;rep} = \sum \eta_{si} A_{si} q_{s;i;rep}$. Bearing capacities estimations are based on a representative resistance-settlement curve, which uses empirical limit settlements for $q_{b;rep}$ and $q_{s;rep}$ full mobilization and empirical correlations for ultimate $q_{b;rep}$ and $q_{s;rep}$ values that depend on limit settlements and CPT or c_u values.

AFNOR: NF P 94-262 classifies Close-ended Pipe Piles (CPP) to "class 4" and Open-ended Pipe Piles (OPP) to "class 5". It employs $q_{b;rep} = k_c\ q_{ce}$ and $q_{s;rep} = \alpha f_{soil} \leq q_{smax}$, where q_{ce} is an equivalent CPT value, k_c varies according to soil type, pile geometry and pile class, while $0.2 \leq \alpha \leq 2.25$ and q_{smax} vary according to soil type and pile class.

BS 8004 classifies CPP to "high displacement class" and OPP to "low displacement class", which refer to the degree of installation disturbance. It allows calculation from SPT, CPT (both used herein) or soil strength data. The CPT calculation is $R_{b;rep(0.1)} = A_b c_{b;0.1} q_{c;b;rep}$ and $R_{s;rep} = \sum c_{s;i} A_{s;i} q_{c;i;rep}$, where $q_{b;0.1}$ is the measured cone resistance over 1.5D depth below base, $q_{c;i}$ is the measured cone resistance within the layer, while $c_{b0.1}$ and $c_{s;i}$ are empirical coefficients that depend on soil pile type and can be estimated from Tables. The SPT calculation is $R_{b;rep(0.1)} = A_b n_{b;0.1} p_{ref} N_b$ and $R_{s;i} = A_s n_{s;i} p_{ref} N_i$, where p_{ref} = 100 kPa, $n_{b;0.1}$ and $n_{s;i}$ empirical coefficients that depend on soil and pile type (typical tabulated values are given), N_b and $N_{s;i}$ the uncorrected N_{SPT} at the base and in layer i respectively.

Tables 1 and 2 summarise the Japanese codes AIJ (2019) of Architectural Institute, JRA (2017) of Road Association, MLIT (2020) of Ports and Harbours Bureau and RTRI (2012) of Railway TRI.

Table 1. q_b and q_s based on Japanese codes (in kPa) (1/2).

Code	Type	Soil type: Sand	Soil type: Clay
Railway	q_b	$210N$ (≤10000)	6.3c or $75N$ (≤20000)
		CPP: N = mean N-value $3D_o$ below pile tip	
		$175N$ (≤ 8000)	$55N$ or $5.5s_u$ (≤16000)
		OPP with w/ D_o≦0.8 m and l/D_o >5: N = N-value of ground at 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 pile tip, N_2 = N-value of ground at pile tip, D_o = outer pile diameter	
		$35(l/D_o)N$ (≤8000)	$11(l/D_o)N$ or $1.1(l/D_o)s_u$ (≤16000)
		OPP with w/ D_o ≦0.8 m and l/D_o≦5: N = N-value of ground at pile tip	
		$(140/D_o)N$ (≤8000)	$(44/D_o)N$ or $(4.4/D_o)s_u$ (≤16000)
		OPP with w/ D_o > 0.8 m and l/D_o >5: N = N-value of ground at pile tip	
		$(28/D_o)(l/D_o)N$ (≤8000)	$(8.8/D_o)(l/D_o)N$ or $(0.88/D_o)(l/D_o)s_u$ (≤16000)
		OPP with w/ D_o > 0.8 m and l/D_o≦5: N = N-value of ground at pile tip	
	q_s	$3N$+30 (≤150)	$6N$ or $0.4s_u$ (≤120)
		$3N$ (≤120)	$6N$ or $0.4s_u$ (≤120)

Table 2. q_b and q_s based on Japanese codes (in kPa) (2/2).

Code	Type	Soil type: Sand	Soil type: Clay
Port	q_b	$300\eta N$ (≤15000)	$6s_u$
		$N = (N_1+N_2)/2$, N_1 = N-value of ground at pile tip, N_2 = mean N-value $4D_o$ above pile tip, η = plugging efficiency	
	q_s	$2N$ (≤100)	$1s_u$ (≤100)
Archi.	q_b	$300\eta N$ (≤18000)	$6s_u$ (≤18000)
		$\eta = 0.16(L_B/D_i)$ for $2 \le L_B/D_i \le 5$; $\eta = 0.8(L_B/D_i)$ for $L_B/D_i > 5$; L_B = embedment into bearing stratum, D_i = inner pile diameter	
	q_s	$2N$ (≤100)	$0.8s_u$ (≤100)
Road	q_b	$130N$ (≤6500)	$90N$ (≤4500)
	q_s	$5N$ (≤100)	$6N$ or $1s_u$ (≤70)

4 COMPARISON OF PILE RESISTANCES

Results from an open-ended steel pipe pile (SPP) at Jibanshikenjo test site in Sashima, Ibaraki Prefecture, Japan are considered. It had an outer diameter of 318.5 mm, a wall thickness of 6.6 mm and an embedment length of 11.0 m. The Static Load Test (SLT) and Rapid Load Tests (RLTs) carried out are summarized in Figure 1. The RLT instrumentation is shown in Figure 2. To estimate the soil resistance R_{soil} (= static soil resistance R_w + dynamic soil resistance R_d) and R_w from the measured values of applied load F_{rapid} and pile head acceleration α, UnLoading Point Connection Method invoking CASE method (ULPC_CM) (Lin et al., 2023a) was used. The relative loading duration $T_r = t_L/(2L/c)$ (t_L= loading duration, L = pile length, c = bar wave velocity in pile) in RLTs was about 5 according to JGS (2002).

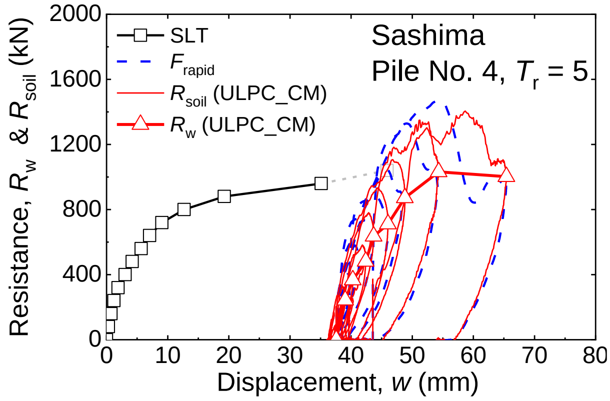

Figure 1. Static load-displacement relations from SLT and RLTs.

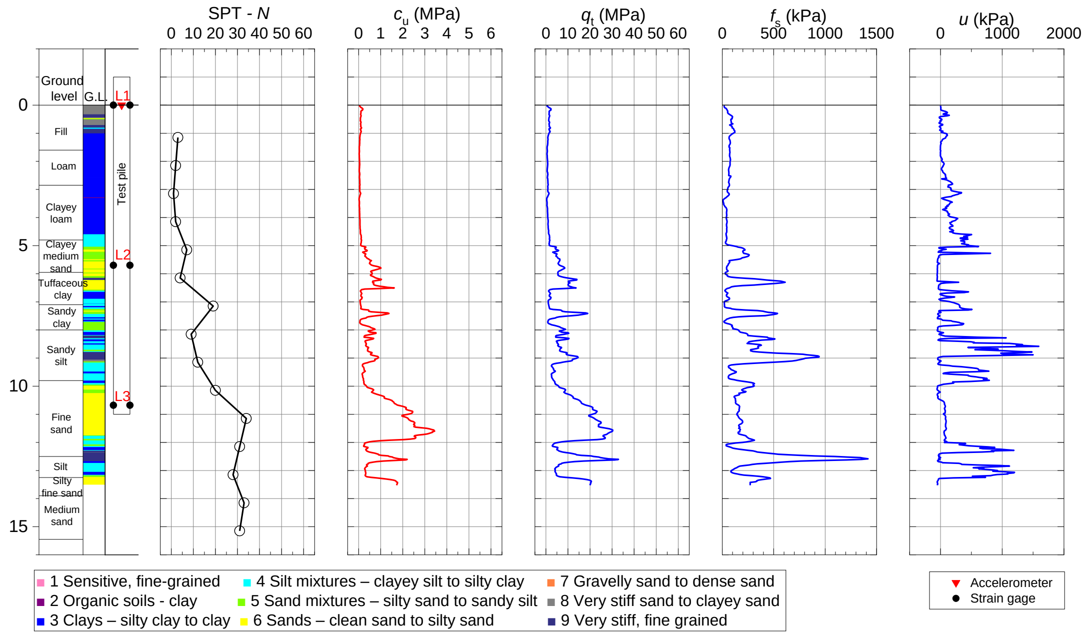

Figure 2. Site soil profile (undrained strength c_u is computed from q_t).

Figure 2 presents the soil profile and the in-situ results: a) SPT *N*-values obtained at 1 m intervals and b) electric Cone Penetration Test (CPT) measurements of corrected cone tip resistance q_t, sleeve friction f_s and pore water pressure u at 20 mm intervals. The undrained shear strength c_u was estimated using q_t. Notice that the estimated c_u is valid for only clayey soil layers.

Three EN 1997 National Annexes, namely DIN (including "Recommendations on Piling", DGGT (2013)), AFNOR and BSI and four Japanese codes, are applied to the test site results.

4.1 Calculation by SPT *N*-value

Four Japanese codes and EN 1997 Annex BS have been used. Figure 3 shows the distributions with depth of shaft resistance τ_f (or $q_{s;rep}$) from static Load Tests (SLT), Rapid Load Tests (RLT) with ULPC_CM and SULPC interpretations (Lin et al., 2023b), and various design codes. SULPC is an extension of ULPC. If the dynamic signals are measured at several levels of a pile, the pile is divided into several pile segments. ULPC interpretation is applied to each pile segment to obtain the static force-displacement relation of the segment. Response of the whole pile subjected to static pile head load is then calculated through a one-dimensional FEM using the static response of pile segments previously obtained (Kamei et al., 2023).

Notice that when the empirical equation using only cohesion (undrained shear strength) c is specified in the Japanese codes, $c = 6.25N$ (kPa) was assumed.

In Figure 3, the dotted lines are the shaft resistance τ_f estimated from the various design codes. The solid lines indicate the average values of τ_f along the pile segment, specifically Seg. 1 and Seg. 2. The thick solid lines are the measured τ_f in SLT and RLTs.

Concerning RPL, to estimate the soil resistance on each pile segment, ULPC_CM interpretation analysis was carried out using the measured signals at each measurement level (L1, L2 and L3). When the signal measured at L1 are used, the soil resistance below L1 is obtained. Similarly, when the signals measured at L2 are used, the soil resistance below L2 is obtained. When signals measured at L3 are interpreted, the soil resistance is the pile tip resistance. Hence, the soil resistance acting on each segment was obtained.

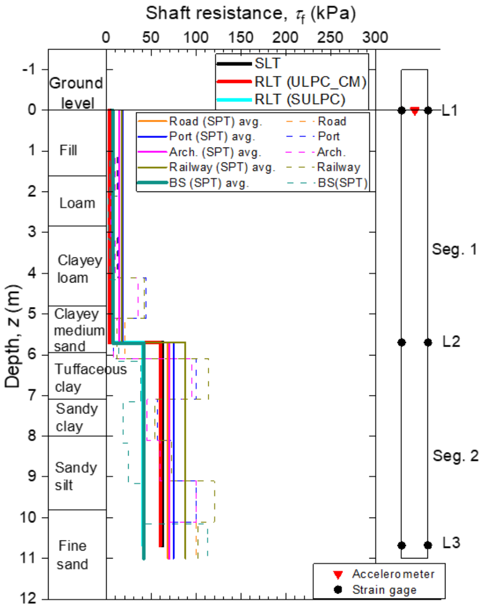

Figure 3. Distributions of shaft resistance τ_f from SLT, RLT and design codes (SPT).

Figure 4 shows the comparison of shaft resistance τ_f of two pile segments from SLT, RLT and the design codes. While Japanese codes show no significant differences, they tend to overestimate the SLT result. On the other hand, the shaft resistance τ_f from BS and RLTs are almost equal to the SLT result.

Figure 5 shows the comparison of maximum total shaft resistance Q_s and maximum total tip resistance Q_b from SLT, RLT and the design codes. The trend of Q_s is similar to that described in Figure 4. There is a wide variation in Q_b from the design codes. 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.

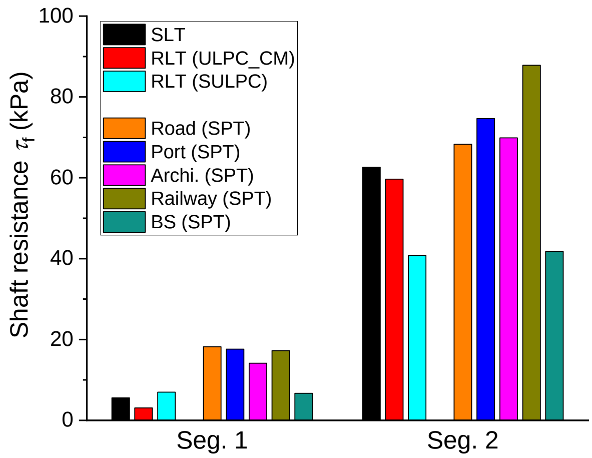

Figure 4. Comparison of average shaft resistance τ_f of two pile sections from SLT, RLT and design codes (SPT).

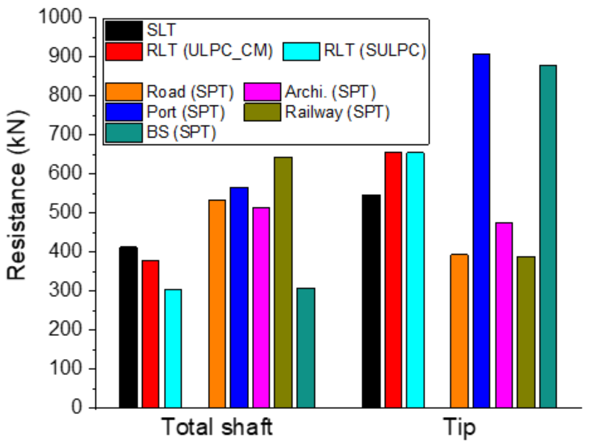

Figure 5. Comparison of maximum shaft resistance Q_s and maximum tip resistance Q_b from SLT, RLT and design codes (SPT).

4.2 Calculation by CPT

The Unified CPT method (Lehane et al., 2022a, b) and three EN 1997 Annexes (BSI, AFNOR, DIN) are applied to compare them to shaft resistances and tip resistance from SLT and RLT. The shaft resistances are estimated at 0.02 m intervals of CPT measurements. When CPT-based methods were used, soil classification from the borehole investigation (SPT) (Fig. 2) was used. Loam, clayey loam, tuffaceous clay and sandy clay were classified as "clay", and the other soil layers were classified as "sand".

Figure 6 shows the distributions with depth of shaft resistance τ_f from the SLT, RLT with ULPC_CM and SULPC interpretations (Lin et al., 2023b) and the various CPT codes (dotted lines). The solid lines indicate the average values of τ_f along the pile Seg. 1 and Seg. 2. Notice a coefficient F_{st} was set as 0.3 in the Unified CPT method.

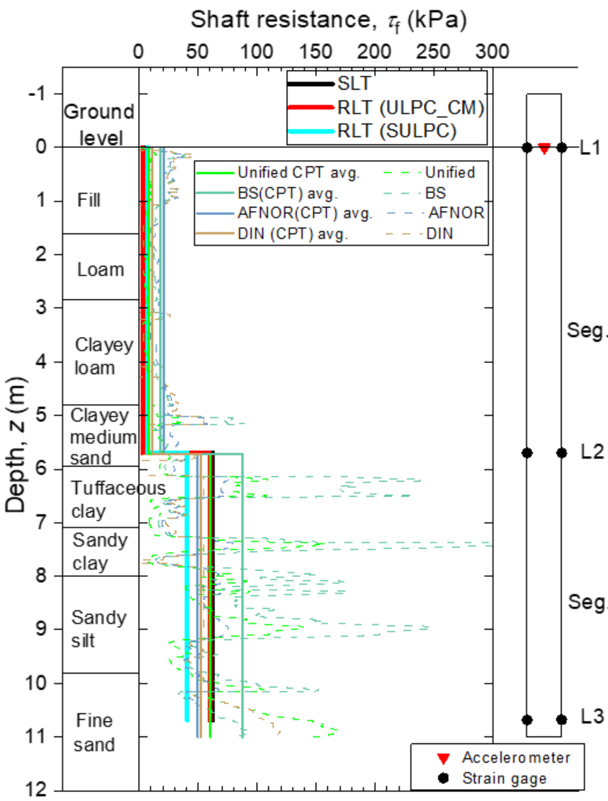

Figure 6. Distributions of shaft resistance τ_f from SLT, RLT and design codes (CPT).

Figure 7 shows the comparison of shaft resistance τ_f of two pile segments from SLT, RLT and the design codes. Shaft resistance from BS tends to overestimate the result of SLT. The shaft resistance τ_f from Unified CPT, DIN and RLT are almost equal to the SLT result.

Figure 8 shows the comparison of maximum total shaft resistance Q_s and maximum total tip resistance Q_b from SLT, RLT and the CPT codes. The Q_s of RLT, Unified CPT, AFNOR and DIN are almost equal to the SLT result. However, all the Q_b from CPT code underestimate the SLT result.

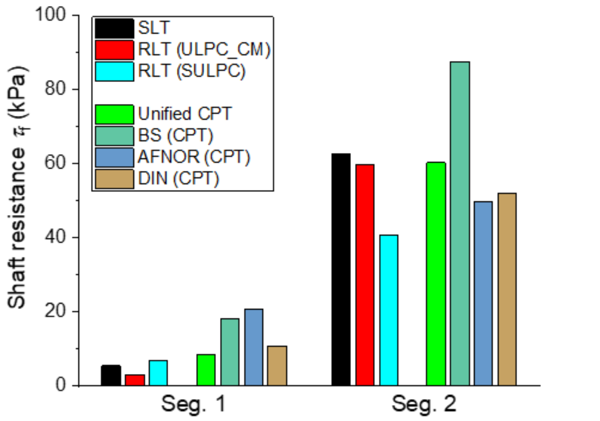

Figure 7. Comparison of average shaft resistance τ_f of two pile sections from SLT, RLT and design codes (CPT).

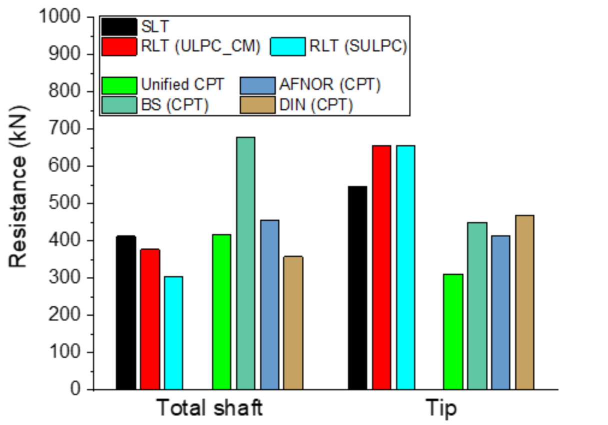

Figure 8. Comparison of maximum shaft resistance Q_s and maximum tip resistance Q_b from SLT, RLT and design codes (CPT).

5 CONCLUSIONS

Pile SLT and RLT results at the Jibanshikenjo test site in Sashima were compared to the pile resistance estimated based on SPT and CPT measurements for different European and Japanese codes. Test piles SLT and RLT showed close agreement. The different empirical pile resistance estimations from SPT and CPT varied considerable. Despite that some methods gave good results, e.g. BS for shaft resistance from SPT, Unified CPT, AFNOR and DIN for shaft resistance from CPT, there was not any consistent trend, especially for the tip resistance. SLT and RLT must be considered more accurate, while the empirical methods should always consider local experience and preferably be compared to SLT or RLT results.

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