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Improving dynamic soil parameters and advancing the pile signal matching technique

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ABSTRACT

The pile signal matching technique widely used for estimating vertical resistances of piles during construction is highly influenced by the assumed dynamic soil parameters. Due to the lack of understanding and supporting data, constant soil parameters for the entire pile length have been routinely used. This practice is unrealistic and compromises the signal match quality. Using recently completed field tests, this paper develops empirical equations for dynamic soil parameters in terms of measureable soil properties and proposes an improved signal matching technique, thereby allowing for better match quality.

1. Introduction

A challenge associated with driven pile foundations is the ability to accurately verify pile resistance at the end of driving (EOD) so that they can be constructed cost-effectively. Pile resistance in the field is verified using expensive and time-consuming static load tests, less efficient dynamic driving formulas that typically produce unnecessarily conservative results [1], or reliable and cost-effective dynamic analysis methods [2]. For this reason, dynamic analysis methods, such as the CAse Pile Wave Analysis Program (CAPWAP), developed by Rausche et al. [2], have been widely used as the construction control method for pile driving. However, the accuracy of dynamic analysis methods is highly influenced by dynamic soil parameters, in which unrealistic constant values for the entire pile length have been routinely used. To improve the reliability of dynamic analysis methods, this paper focuses on quantifying more realistic dynamic soil parameters as a function of soil types and properties.

Pile resistance verification using CAPWAP is performed by matching the measured pile force and velocity signals collected from a Pile Driving Analyzer (PDA) with the corresponding signals simulated based on one-dimensional soil–pile model proposed by Smith [3], as shown in Fig. 1. In this model, a pile is represented by a series of masses (m) connected with elastic–plastic springs representing the pile stiffness while the surrounding soil is represented by a series of linear-plastic springs and linear dampers. The accuracy of pile resistance verification using CAPWAP based on this model is highly dependent upon the proper selection of two dynamic soil parameters, i.e., quake value (q) that defines the soil stiffness (k) represented by a linear-plastic spring, and damping factor (J) that determines the viscous damping coefficient (c) represented by a linear damper [4]. Although varying soil types with different soil properties typically exist along a pile, constant shaft quake (q_s) and shaft damping factor (J_s) are currently used in CAPWAP analysis to define the soil characteristics along the pile shaft [4]. Similar to the dynamic shaft parameters, constant toe quake value (q_T) and toe damping factor (J_T) are also used [4].

To describe the soil-damping characteristic along a pile and at pile toe, Smith [3] estimated the damping coefficient (c) as a product of a static soil resistance (R_s along the pile shaft or R_T at pile toe), a damping factor (J), and an instantaneous pile velocity (v). Since the static soil resistance describes the geostatic mode of the pile–soil system and the pile velocity is measured using PDA, the damping characteristic of the surrounding soils can be reasonably related to the damping factor.

Due to limited dynamic data for correlation studies, Smith [3] recommended constant dynamic parameters for the entire pile length embedded in any soil type as detailed in Table 1. Approximately a decade later, Coyle et al. [5] estimated a set of dynamic parameters for three different soil types (i.e., clay, sand, and silt) from full-scale pile load tests. Compared with Smith's

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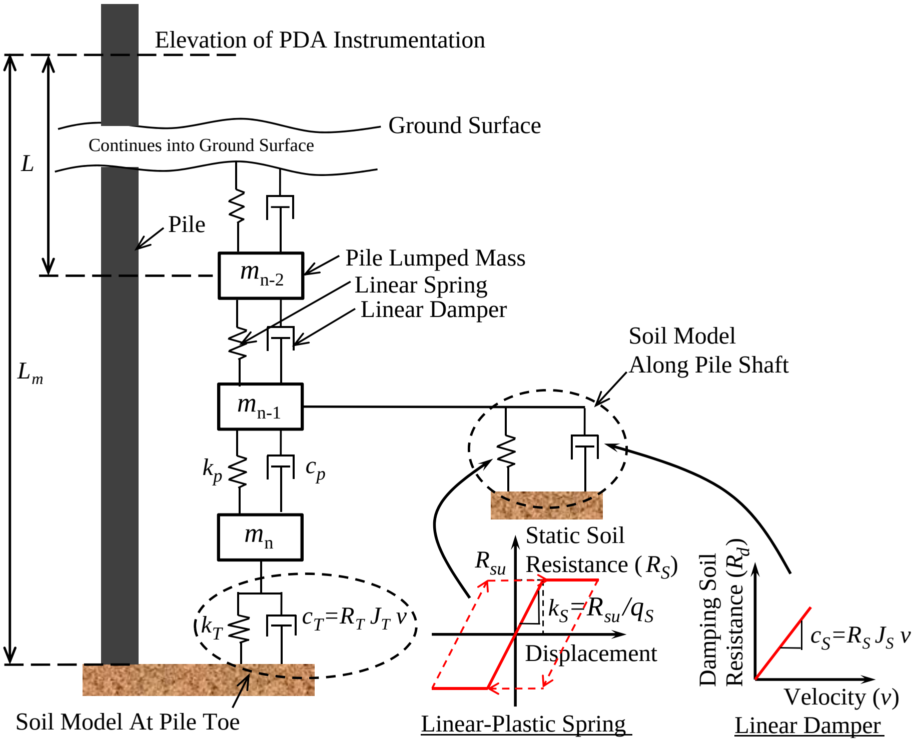


Fig. 1. One-dimensional soil–pile model (adapted after Pile Dynamics Inc. [4]).

Table 1
Summary of previously suggested dynamic soil parameters.

Reference	Damping factor (s/m)		Quake value (mm)	
	Shaft (J_s)	Toe (J_T)	Shaft (q_s)	Toe (q_T)
Smith [3]	0.16	0.49	2.54	2.54
Coyle et al. [5]	0.66 for clay 0.16 for sand 0.33 for silt	0.03 for clay 0.49 for sand 0.49 for silt	2.54	2.54
Hannigan et al. [6]	0.66 for cohesive soil 0.16 for non-cohesive soil	0.49	2.54	$D/120$ for dense and hard soil $D/60$ for soft soil

D – pile diameter/width.

recommendations, Coyle et al. [5] proposed as much as two to four times higher shaft damping factors for silt and clay and a negligibly small toe damping factor for clay, which suggest that dynamic soil parameters are not constant but dependent on soil types. These authors acknowledged that an extensive data set was not available at the time for characterizing the dynamic parameters and therefore suggested the use of more accurate parameters, if available, in the future. In the absence of further refinements to dynamic soil parameters, Hannigan et al. [6] adopted recommendations of Coyle et al. [5] with an adjustment for the toe quake value in terms of pile diameter/width (D). Hannigan et al. [6] believed that damping factors are not constant for a given soil type, and a higher value may be more appropriate for soft soils than hard rock. Based on their accumulated pile driving experience and observations, Hannigan et al. [6] noted that damping factors should also be expected to vary with time after the EOD, and higher dynamic parameters may be appropriate for the analyses modeling the beginning of restrike (BOR) condition. However, due to the lack of dynamic pile measurements and quantitative analyses, their hypotheses have not been validated, and constant parameters as listed in Table 1 have been used for dynamic analyses.

Based on a series of dynamic load tests on a 61-mm diameter steel, smooth, close-ended pipe pile driven in a fine to medium poorly grade sand, compacted to three different relative densities of 35%, 50% and 70%, Malkawi and Ayasrah [7] concluded that damping factors (J) are inversely proportional to sand relative density and static sand resistance. Nonetheless, relationships between dynamic soil parameters and measureable soil properties were not established due to the lack of extensive dynamic measurements and good quality data sets.

Liang [8] conducted a statistical analysis on the dynamic soil parameters using a database of 611 driven piles collected by Paikowsky et al. [9]. The dynamic soil parameters summarized in Table 2 were estimated by Liang using the routine CAPWAP signal matching procedure, in which constant dynamic soil parameters were used for the entire subsurface. Considering two soil types (i.e., sand and clay) and when the dynamic pile testing was performed (i.e., EOD and BOR), Table 2 reveals that the quake values varied minimally with the soil type and schedule of dynamic testing, while the damping factors were found to be influenced more by when the dynamic testing was done rather than the soil type. The relatively high standard deviation indicated a large scatter in

Table 2
Statistical summary for dynamic soil parameters (after Liang [8]).

Soil type	Parameters	Statistical summary	EOD condition	BOR condition
Sand	J_s (s/m)	Mean	0.53	0.67
		Standard deviation	0.53	0.53
	q_s (mm)	Mean	3.0	3.0
		Standard deviation	4.6	3.8
Clay	J_s (s/m)	Mean	0.43	0.73
		Standard deviation	0.40	0.53
	q_s (mm)	Mean	2.8	3.0
		Standard deviation	1.3	1.5

the dynamic soil parameter estimation, which likely has reduced the accuracy of the pile resistance estimation obtained from CAPWAP. Compared with the suggested parameters for sand given in Table 1, higher J_s and q_s values are given in Table 2. For clay, the J_s values at EOD are lower while the J_s values at BOR and q_s are higher than that given in Table 1.

The aforementioned reviews conclude that although many investigations on dynamic soil parameters have been conducted by different researchers [3–10] for more than three decades, no significant advancements have been accomplished. This setback is attributed to (1) the routine signal matching technique used in the CAPWAP analysis, (2) lack of high quality field data, and (3) a broad representation of dynamic soil behavior by the Smith model.

The main objective of this paper is to establish a more realistic distribution of dynamic soil parameters corresponding to the soil stratigraphy based on an improved signal matching technique. Using the results of six recently completed, full-scale pile load tests conducted throughout the State of Iowa, USA, by Ng et al. [11,12], empirical relationships for dynamic soil parameters were established with relatively high accuracy. These relationships were confirmed by the improvement of signal matching and were further validated using an independent data set obtained from a steel H-pile embedded in a mixed soil profile. The influences of pile setup on the estimation of cohesive soil parameters are also discussed.

2. Routine CAPWAP procedure

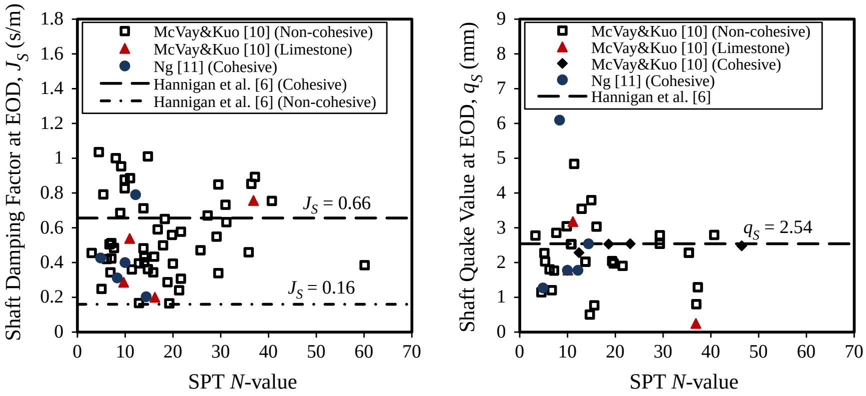
The signal matching technique routinely used during CAPWAP analyses emphasize achieving the best signal matching using constant values for shaft damping factor and quake along the entire pile length, regardless of the soil profile. The accuracy of signal matching is evaluated in terms of a match quality (MQ) as given by Eq. (1), which is the normalized sum of the absolute values of the differences between computed (P_c) and measured (P_m) pile responses (i.e., pile force, velocity, or WaveUp defined by Eq. (3)) at each time interval, divided by the maximum pile top responses (P_x) [4]. Any unmatched pile set (i.e., the absolute difference between measured and computed pile penetration per hammer blows ($\mathit{\Delta}_{set}$) equals or exceeds 1 mm) will penalize the MQ by $\mathit{\Delta}_{set} - 1$ as illustrated in

$$MQ = \sum_{period}\sum_{time}\left|\frac{P_m - P_c}{P_x}\right| + (\mathit{\Delta}_{set} - 1) \tag{1}$$

The limitation of the routinely used technique is that the outcome of CAPWAP analysis is not unique and is influenced by the magnitude of the dynamic soil parameters, shaft and toe resistances that can be adjusted arbitrarily in striving to achieve the best match. Because of the indeterminate nature of the routine signal matching technique, dynamic soil parameters cannot be uniquely quantified in terms of measurable soil properties, potentially explaining the reason for drastically different dynamic soil parameters recommended in Table 1. A large degree of scatter in the soil parameters is typically produced, as illustrated in Fig. 2 based on results collected by McVay and Kuo [10] and Ng et al. [11]. Although CAPWAP has an extended input domain allowing the possibility of accounting for varying dynamic soil parameters along the pile length, this capability is rarely used due to the absence of reliable methods for quantifying the dynamic soil parameters.

3. Improved signal matching technique

To accomplish the objective of uniquely quantifying the dynamic soil parameters and eliminating the burden of striving to adjust a significant number of unknowns during the CAPWAP analysis, the static soil resistances (R_s) at each soil segment alongside a pile and at pile toe are estimated using the Schmertmann's [12] method based on unit skin friction (f_s) and unit tip resistance (q_c) data obtained from the Cone Penetration Test (CPT). The CPT method is chosen among other static analysis methods because it is a direct method for more accurate pile resistance estimations. The estimated soil resistances using the Schmertmann's [12] method are proportionally adjusted so that the total resistance obtained from the Schmertmann's [12] method matches the total computed resistance using the routine CAPWAP technique. This approach not only generates a realistic distribution of the static resistance, but also ensures comparable pile resistance estimation using the routine CAPWAP procedure. The next step is to identify the dynamic soil parameters of each soil segment described in the one-dimensional



(a) Shaft damping factor (b) Shaft quake value

Fig. 2. Dynamic soil parameters as a function of SPT N-value.

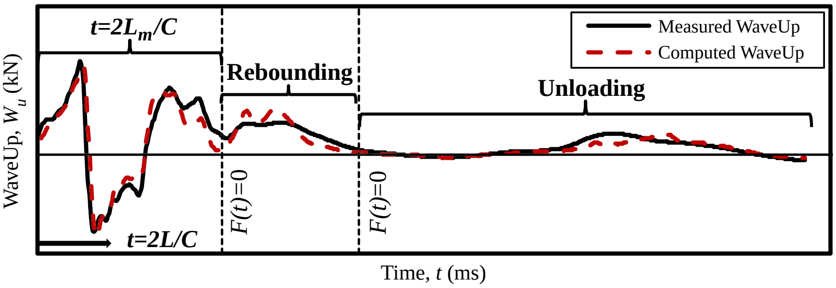


Fig. 3. Comparison of measured and computed upward traveling wave forces (W_u).

pile–soil model in Fig. 1. Using the concept of wave propagation, the influence of a series of soil segments, from which the stress wave is reflected, can be identified from the measured pile response at a time interval t determined by

$$t = \frac{2L}{C} \tag{2}$$

where L is the distance from the PDA instrumentation near the pile top to the soil segment of interest (see Fig. 1), and C is the pile wave speed. Hence, the dynamic characteristic of the specified soil segment can be determined by matching the PDA recorded pile response with the CAPWAP computed response up to the time t that corresponds to the location of the specified soil segment. This approach should begin with the soil segment closest to the ground surface and repeat on consecutive soil segments from the top to the bottom of pile length. The dynamic parameters obtained from the previous CAPWAP analysis for the preceding soil segments are used in the matching process including the current soil segment. Following the recommendation of the routine technique [4], the MQ of the improved signal matching technique is evaluated in terms of an upward traveling wave force (WaveUp or W_u) presented in Fig. 3

$$W_u = \frac{F(t) + Zv(t)}{2} \tag{3}$$

where $F(t)$ is the measured or estimated pile force near pile top at time t, Z is the pile impedance, and $v(t)$ is the measured or estimated pile velocity near the pile top at time t. After completing the matching processes up to the final soil segment at a time interval of $2L_m/C$, where L_m is the entire wave traveling distance (see Fig. 1), a preliminary distribution of soil parameters is determined. At this point, the match process has not covered the entire time duration but up to $2L_m/C$. To account for the effect of dynamic soil parameters in the matching process for both rebounding and unloading zones as shown in Fig. 3, the time of analysis is extended beyond $2L_m/C$ in CAPWAP to include the durations for the rebounding and unloading. This preliminary distribution of dynamic soil parameters is further refined and adjusted proportionally along the shaft until the best match is achieved. Every adjustment to the dynamic soil parameters will follow by a single match analysis using the F2 function in CAPWAP, and a new calculated MQ will be displayed. It is noted that the automatic CAPWAP (AC) analysis should not be performed as this analysis will distort the distributions of both dynamic soil parameters and pile resistances.

4. Summary of full-scale pile tests

The results for six of the ten, full-scale pile load tests recently completed on driven steel H-piles throughout Iowa, USA, are utilized to correlate the dynamic soil parameters using the improved signal matching technique. The test data is publically available at the project website (http://srg.cce.iastate.edu/lrfd/). During pile installation and restrikes, PDA strains and accelerations were collected, and CAPWAP analyses were subsequently performed at each test site. Standard Penetration Test (SPT) and Cone Penetration Test (CPT), as well as laboratory soil characterizations were completed. Table 3 summarizes the pile, hammer and soil information for each test pile, as well as the measured pile capacity determined from static load test (SLT) based on the Davisson criteria [13]. Table 4 summarizes the schedule of dynamic restrike tests and the estimated pile capacities at the EOD and last restrike using the routine CAPWAP procedure.

Five test piles embedded in cohesive soil profiles, which were identified as ISU2, ISU3, ISU4, ISU5 and ISU6, were selected for quantifying the dynamic cohesive soil parameters. Most of the cohesive soil layers along these test piles were low plasticity clay (CL), classified in accordance with the Unified Soil Classification System (USCS). Although ISU6 was embedded in mostly cohesive soil layers, a cohesionless soil layer, referred to as silty sand (SM), was presented between 4.02 m and 6.34 m below the ground elevation. The dynamic data of this SM layer at ISU6 along with the test data of ISU9, which was installed in a cohesionless soil profile with mostly well-graded sand (SW) and poorly graded sand (SP), were used for quantifying the dynamic cohesionless soil parameters. Beside the six test piles, an independent test pile ISU8 with completed SPT and CPT data was selected for the validation of the estimated parameters. The remaining three test piles were not chosen for the following reasons: ISU1 had insufficient dynamic data, ISU7 was installed in a mixed soil profile and ISU10 had insufficient CPT data. The detailed summary of measured soil properties (i.e., q_c, f_s, friction ratio (FR) and uncorrected SPT N-value), soil resistance (R_s) and dynamic soil parameters (i.e., J and

Table 3
Summary of the chosen test piles.

Test pile	Pile type	Emb. pile length (m)	Soil profile	Hammer types	Time of last restrike after EOD (days)	Time of SLT after EOD (days)	SLT measured pile capacity (kN)
ISU2	HP 250 × 63	17.0	Cohesive	Delmag D19-42	3	9	556
ISU3	HP 250 × 63	15.5	Cohesive	Delmag D19-32	2	36	667
ISU4	HP 250 × 63	17.3	Cohesive	Delmag D19-42	5	16	685
ISU5	HP 250 × 63	17.3	Cohesive	Delmag D16-32	8	9	1081
ISU6	HP 250 × 63	17.4	Cohesive	Delmag D19-42	10	14	947
ISU8	HP 250 × 63	17.4	Mixed	Delmag D19-42	5	15	721
ISU9	HP 250 × 63	15.1	Cohesionless	APE D19-42	10	25	703

Table 4
Schedule of dynamic restrike tests and estimated pile capacity using routine CAPWAP procedure.

Test pile	Restrike after the EOD (days)								Estimated pile capacity using routine CAPWAP (kN)	
	1st	2nd	3rd	4th	5th	6th	7th	8th	EOD	Last restrike
ISU2	0.17	0.92	2.97	–	–	–	–	–	359	578
ISU3	0.0028	0.007	0.017	1.11	1.95	–	–	–	440	658
ISU4	0.0041	0.016	0.041	0.74	1.74	4.75	–	–	453	685
ISU5	5.38E−3	0.013	0.048	0.92	2.90	7.92	–	–	790	1088
ISU6	1.60E−3	0.004	0.012	0.07	0.83	2.82	6.79	9.81	644	937
ISU8	7.07E−3	0.011	0.039	0.97	3.97	4.95	–	–	621	710
ISU9	3.87E−3	0.011	0.038	0.69	2.87	9.77	–	–	751	688

q), which were estimated based on the improved matching technique along the pile length and at the toe of test pile ISU5, are presented in Table 5. Similar details for other test piles are reported in Ng et al. [11]. Table 5 clearly shows that both J and q values are not constant as suggested in Table 1. The R_s value at each soil segment was estimated using Schmertmann's [12] method and adjusted proportionally to yield a total resistance of 790 kN that matched the estimated resistance based on the routine CAPWAP single matching technique. It is important to note that the dynamic soil parameters in Table 5 represent the soil characteristics at the EOD, because PDA pile responses collected at the EOD were used in this signal matching. Likewise, dynamic soil parameters representing the soil characteristics at the BOR were determined using the PDA measurements collected at the BOR.

5. Recommended shaft dynamic soil parameters

5.1. SPT approach

Assimilating all dynamic parameters of the five test piles in cohesive soils (i.e., ISU2 to ISU6) as summarized in Table 5 for ISU5, relationships between uncorrected SPT N-value and shaft damping factors (J_s) as well as shaft quake value (q_s) were established in Figs. 4 and 5, respectively. Uncorrected SPT N-values that included the effect of overburden soil were used in the correlation analyses. To enhance the correlation studies, an average dynamic soil parameter was computed from the same SPT N-value. For instance, referring to the estimated J value of 0.59 s/m given in Table 5 for test pile ISU5 and 0.50 s/m for test pile ISU6 that correspond to the same average SPT N-value of 22, an average J value of 0.55 s/m was determined as shown in Table 6 and plotted as a single solid circle in Fig. 4. Unlike the constant parameters suggested by Smith [3] and Hannigan et al. [6] in Table 1, these figures clearly show that the J_s value increases with SPT N-value, while the q_s value decreases with the SPT N-value (solid lines) for cohesive soils.

Using the PDA records obtained from ISU5 and ISU6 at BOR, which have comparable restrike times of 8 and 10 days, relationships between the SPT N-value and J_s as well as q_s were included for BOR in Figs. 4 and 5. The numerical values are shown in Table 6. Unlike the constant values currently used for EOD, Fig. 4 shows that the J_s value for cohesive soils at the BOR also increases with the SPT N-value. In addition, the J_s values for BOR are greater than those found for EOD with differences increasing with increasing SPT N-value. These two phenomena are believed to be due to the influence of pile setup. Fig. 5 shows that the q_s value for cohesive soils at the BOR also decreases with the SPT N-value, while the effect of pile setup increases the magnitude of the q_s value.

Similar correlation studies between EOD and BOR conditions were performed on cohesionless soil using results of test piles ISU6 and ISU9 as summarized in Table 6. Fig. 4 shows that the J_s value for cohesionless soil at the EOD decreases with the SPT N-value, while q_s increases with the SPT N-value in Fig. 5. These relationships again confirm that dynamic soil parameters are not constant for all soil types as suggested in Table 1. Table 7 summarizes the empirical relationships for the shaft dynamic soil parameters based on the SPT approach and their associated coefficient of determinations (i.e., R^2). Generally, good predictions of shaft dynamic soil parameters are seen except for the q_s value obtained for cohesive soils at BOR. The corresponding relatively low R^2 of 0.69 in this case is believed to be due to the complexity of pile setup and the variation in restrike times between 2 and 10 days as shown in Table 4. This observation is consistent with the relatively higher degree of scatter of date for the BOR as shown in both figures. Nonetheless, it is important to realize that applying a constant value would have led to a poor estimate for q_s, especially

Table 5
Summary of soil properties, soil resistances, and dynamic soil parameters at EOD for ISU5.

Test pile	Depth below ground (m)	Soil type-USCS	Ave. CPT unit tip resistance, q_c (kPa)	Ave. CPT unit skin friction, f_s (kPa)	Ave. friction ratio, FR (%)	Ave. SPT N-value	Est. and adjusted soil resistance at EOD, R_s (kN)	Damping factor at EOD, J (s/m)	Quake value at EOD, q (mm)
ISU5 (shaft)	0.82	ML/SC	2185	68	3.49	–	33	2.57	0.51
	2.44	CL	857	59	7.06	6	68	0.09	5.59
	4.02		1482	124	8.59	8	71	0.09	4.32
	5.61		1318	110	8.80	9	71	0.08	4.06
	7.19		1779	113	6.37	9	71	0.10	4.06
	8.81		1741	112	6.55	10	72	0.29	3.30
	10.39		1604	97	6.13	22	69	0.59	1.02
	11.98	CL/SC	2334	126	5.35	22	70	1.65	1.78
	13.56	CL	3468	155	4.47	15	77	0.36	1.78
	15.18		3310	128	3.97	13	76	0.32	2.03
	16.76		3310	127	3.72	13	74	0.31	2.03
ISU5 (toe)	16.76	CL	3310	127	–	13	38	1.31	1.02

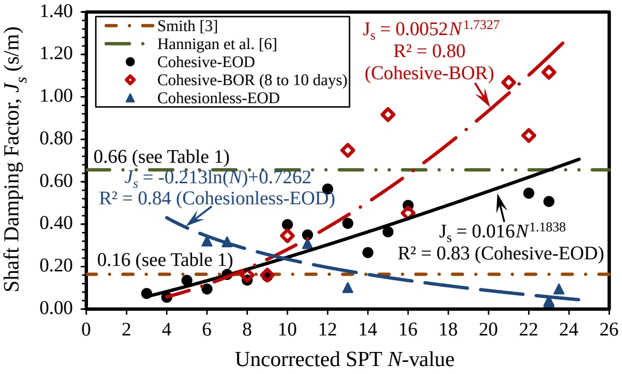


Fig. 4. Variation of shaft damping factor as a function of SPT *N*-value.

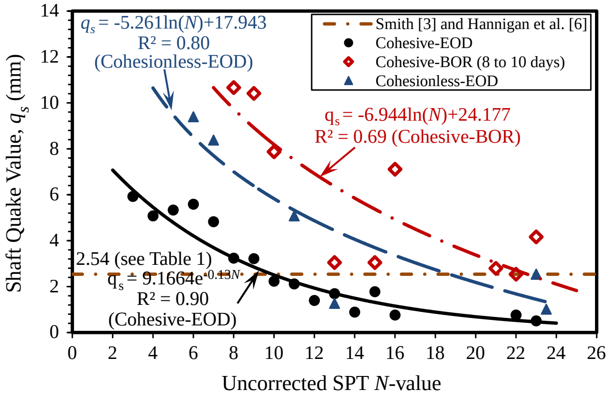


Fig. 5. Variation of shaft quake value as a function of SPT *N*-value.

for soils with *N*-value less than 12. With more data the relationship for q_s can be improved progressively.

5.2. CPT approach

Correlation studies were also performed using the CPT measured soil properties as summarized in Table 5 for ISU5. Despite the recommendations of constant values, no clear relationships can be established between dynamic soil parameters, tip resistances (q_c) and unit skin friction (f_s) as illustrated in Fig. 6. However, unique relationships can be observed in Fig. 7 by plotting the J_s as function of friction ratio (*FR*), which is defined as the ratio of a unit skin friction (f_s) to a total cone tip resistance (q_t). Mayne [14] reported that low *FR* values (less than 1%) were observed in clean quartz sands and siliceous sands, whereas clays and clayey silts of low sensitivity exhibited *FR* values greater than 4%, with sandy silts and silts lying in-between them. Following this

Table 6
Summary of average dynamic soil parameters as a function of uncorrected SPT *N*-value.

SPT *N*-value	EOD condition				BOR condition	
	Cohesive		Cohesionless		Cohesive	
	J_s (s/m)	q_s (mm)	J_s (s/m)	q_s (mm)	J_s (s/m)	q_s (mm)
3	0.07^{a}	5.93^{a}	–	–	–	–
4	0.06^{a}	5.08^{a}	–	–	–	–
5	0.14^{b}	5.33^{b}	–	–	–	–
6	0.09^{d}	5.59^{d}	0.32^{m}	9.40^{m}	–	–
7	0.16^{b}	4.83^{b}	0.32^{m}	8.38^{m}	–	–
8	0.14^{f}	3.24^{f}	–	–	0.16^{l}	10.67^{l}
9	0.15^{g}	3.22^{g}	–	–	0.16^{d}	10.41^{d}
10	0.40^{h}	2.24^{h}	–	–	0.35^{l}	7.87^{l}
11	0.35^{c}	2.12^{c}	0.31^{m}	5.08^{m}	–	–
12	0.57^{i}	1.40^{i}	–	–	–	–
13	0.40^{j}	1.69^{j}	0.10^{m}	1.27^{m}	0.75^{d}	3.05^{d}
14	0.27^{k}	0.89^{k}	–	–	–	–
15	0.36^{d}	1.78^{d}	–	–	0.92^{d}	3.05^{d}
16	0.49^{e}	0.76^{e}	–	–	0.45^{e}	7.11^{e}
21	–	–	–	–	1.07^{d}	2.79^{d}
22	0.55^{l}	0.76^{l}	–	–	0.82^{l}	2.54^{l}
23	0.51^{e}	0.51^{e}	0.035^{e}	2.54^{e}	1.12^{e}	4.17^{e}

[a] ISU2.
[b] ISU3.
[c] ISU4.
[d] ISU5.
[e] ISU6.
[f] ISU2, ISU3, ISU5 and ISU6.
[g] ISU3 and ISU5.
[h] ISU3, ISU4, ISU5 and ISU6.
[i] ISU3 and ISU4.
[j] ISU4 and ISU5.
[k] ISU2 and ISU4.
[l] ISU5 and ISU6.
[m] ISU9.

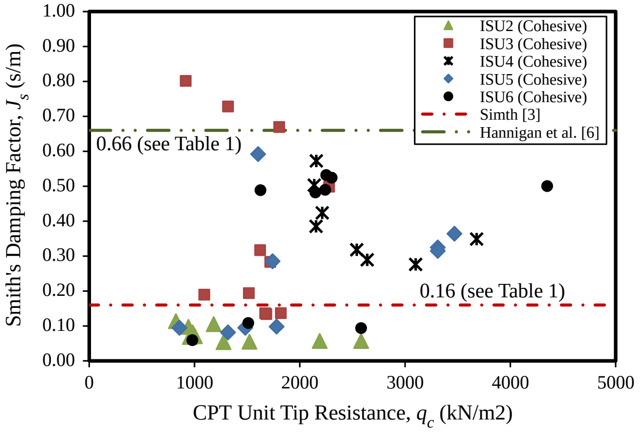


Fig. 6. Variation of shaft damping factor as a function of CPT unit tip resistance.

Table 7
Summary of empirical relationships for shaft dynamic soil parameters.

In situ soil test	Soil types	EOD/BOR	Parameter	Unit	Relationship	R^2
SPT	Cohesive	EOD	J_s	s/m	$J_s = 0.016N^{1.1838}$	0.83
	Cohesive	EOD	q_s	mm	$q_s = 9.1664e^{-0.13N}$	0.90
	Cohesive	BOR	J_s	s/m	$J_s = 0.0052N^{1.7327}$	0.80
	Cohesive	BOR	q_s	mm	$q_s = -6.944\ \ln(N) + 24.177$	0.69
	Cohesionless	EOD	J_s	s/m	$J_s = -0.213\ \ln(N) + 0.7262$	0.84
	Cohesionless	EOD	q_s	mm	$q_s = -5.261\ \ln(N) + 17.943$	0.80
CPT	Dense clay ($N > 9$)	EOD	J_s	s/m	$J_s = -0.286\ \ln(FR) + 0.8426$	0.64
	Soft clay ($N \leqslant 9$)	EOD	J_s	s/m	$J_s = 0.08$	–
	Dense silt ($N > 9$)	EOD	J_s	s/m	$J_s = -0.286\ \ln(FR) + 0.8426$	0.64
	Soft silt ($N \leqslant 9$)	EOD	J_s	s/m	$J_s = 0.08–0.30$	–
	Sand	EOD	J_s	s/m	$J_s = 0.10–0.30$	–
	All soils	EOD	q_s	mm	Vary between 0.2 and 8.4 mm	–

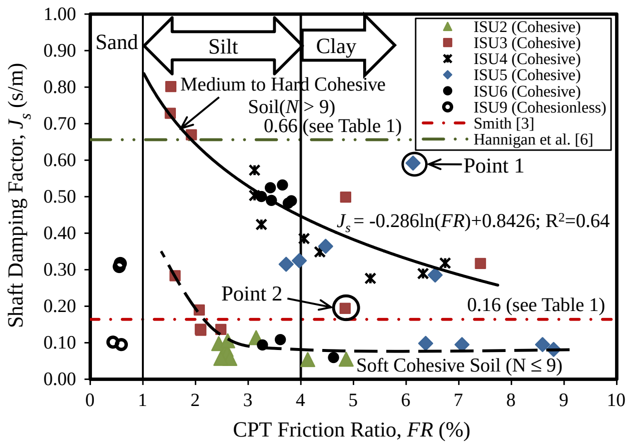


Fig. 7. Variation of shaft damping factor as a function of CPT friction ratio.

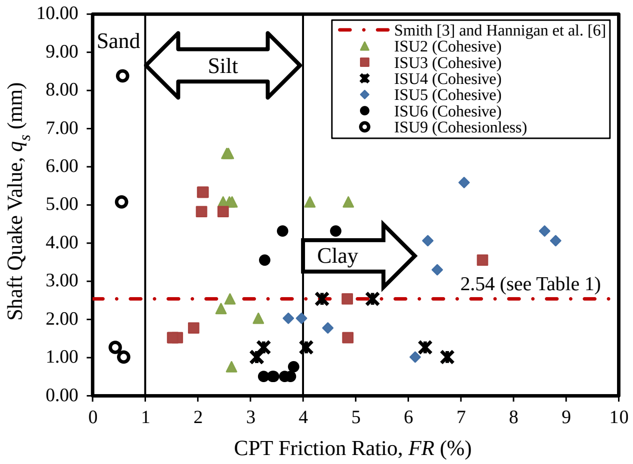


Fig. 8. Variation of shaft quake value as a function of CPT friction ratio.

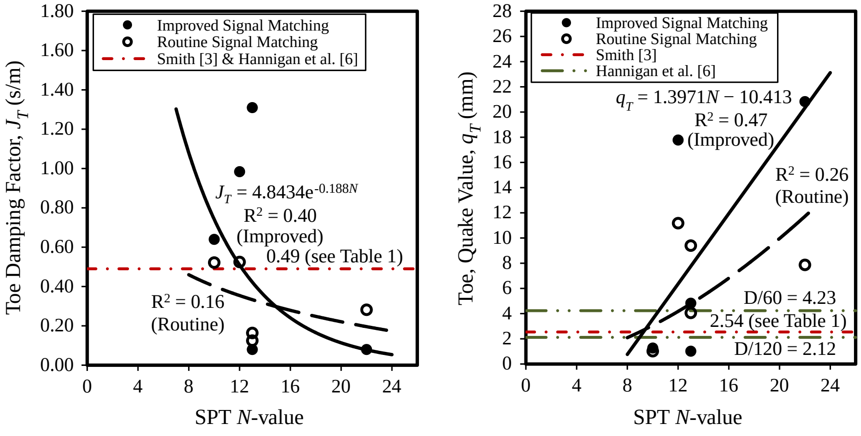
suggestion, Fig. 7 is divided into three soil regions: sand, silt and clay. For medium to dense silt and clay (i.e., $N > 9$), the J_s value decreases with increasing *FR* values. However for soft silt and clay soils (i.e., $N \leqslant 9$), the J_s value decreases from about 0.3 s/m at *FR* of 1.5% to 0.08 s/m at *FR* of 4% (i.e., from sandy silts to silts) and remains almost constant at about 0.08 s/m for clayey silt and clay. Due to limited test data on cohesionless soil, Fig. 7 shows that the J_s values for sand fall between 0.1 s/m and 0.30 s/m. Referring to Table 5, the outliner point 1 obtained from ISU5 represents the soil parameters at 10.39 m, which was a lean clay layer (CL) just above the lean clay to clayey sand layer (CL/SC). At this transitional layer from cohesive to mixed soils, the shaft damping factor (J_s) is likely to be higher and does not fit well in the trend. Likewise, a consistent observation was noted at point 2 obtained from ISU3 representing soil parameters at 2.96 m, which is corresponded to a lean clay layer (CL) just above a lean clay to silty sand layer (CL/SM). Hence, it can be concluded that Fig. 7 is suitable for estimating J_s values for cohesive soils, while higher J_s values may be anticipated in the boundary layer.

Fig. 8 shows that when similar correlation studies were performed on the q_s value with respect to the *FR* value, q_s values vary between 0.2 mm and 8.4 mm, while the variation reduces from sand to clay. This observation also implies that the q_s value is not a constant parameter of 2.54 mm as suggested in Table 1. The suggested shaft dynamic soil parameters based on the CPT approach are summarized in Table 7.

These correlation studies conclude that the empirical relationship established from the SPT approach, which is subjected to a similar, continuous impulsive hammer force as experienced by the pile during driving, provides a better quantification of shaft dynamic soil parameters.

6. Study of toe dynamic soil parameters

Using the SPT approach and the improved signal matching technique, the estimated toe damping factor (J_T) and toe quake value (q_T) for the five test piles in cohesive soils were plotted against the SPT *N*-value in Fig. 9a and b, respectively, using solid circles. Similar comparison with the *FR* was not performed since all pile toes were embedded in cohesive soils. For comparison, the dynamic soil parameters determined from the routine CAPWAP matching technique for the same five test piles were also plotted against the same SPT *N*-value in Fig. 9 using open circles. Compared to the best-fit lines for shaft parameters in Figs. 4 and 5. Fig. 9 shows a relatively lower correlation for toe parameters with R^2 of 0.40 for the J_T value and R^2 of 0.47 for the q_T value. Different fitting trends were chosen, because they give the best correlation (i.e., highest R^2 value). The relatively high variability in the toe parameters was anticipated because (1) only a single toe parameter was used; and (2) the contribution of the end bearing component is small for driven test piles, causes larger error in the estimation of toe parameters. Nonetheless, Fig. 9 shows that the



(a) Toe damping factor (b) Toe quake value

Fig. 9. Toe dynamic soil parameters as a function of SPT *N*-value.

Table 8
Comparison between the routine and improved matching technique in terms of match quality.

Test pile	EOD/BOR	Weighted average SPT *N*-value	Match quality (*MQ*)						Percent improvement (WaveUp) (%)
			Routine CAPWAP technique			Improved CAPWAP technique			
			Force	Velocity	WaveUp	Force	Velocity	WaveUp	
ISU2	EOD	4.85	10.38	6.89	4.48	8.92	6.55	3.60	20
ISU3	EOD	8.33	4.43	3.43	3.47	4.10	3.24	3.48	0
ISU4	EOD	9.96	5.20	2.55	2.68	3.89	2.53	2.64	1
ISU5	EOD	12.17	2.06	1.07	1.16	5.74	0.98	1.04	10
	BOR6	12.17	1.73	1.91	1.42	1.83	1.49	1.39	2
ISU6	EOD	14.38	3.88	2.26	2.16	3.78	2.79	2.08	4
	BOR8	14.38	1.35	1.12	1.22	1.63	1.00	1.19	2
ISU8	EOD	8.60	2.74	2.07	1.96	2.61	2.08	1.59	19
ISU9	EOD	11.23	2.39	2.06	1.96	2.46	1.97	1.80	8

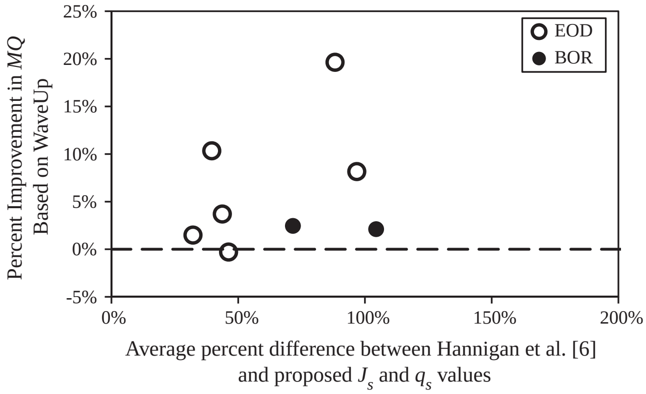


Fig. 10. Variation of percent improvement in *MQ* as a function of average percent difference between Hannigan et al. [6] values given in Table 1 and proposed J_s and q_s values in Table 7.

improved signal matching technique provides a better correlation for toe parameters than the routine signal matching technique. It is realized that more refinement to the proposed trends can be achieved as more data becomes available. Despite the challenges with quantifying toe dynamic soil parameters in terms of measureable soil properties, Fig. 9 clearly indicates that toe dynamic soil parameters do not follow the typical constant value as suggested in Table 1.

7. Validation of recommended dynamic soil parameters

The aforementioned correlation studies not only have provided successful quantification of the dynamic soil parameters in terms of SPT *N*-value, but also the studies have improved the match quality (*MQ*) of each CAPWAP analysis using the improved signal matching technique for the

EOD condition by an average of 7% to as high as 20% for WaveUp records shown in Table 8. Additionally, the match qualities based on the force and velocity records have been improved in most cases as shown in Table 8. Fig. 10 shows the relative percent improvement in the *MQ* as a function of the average percent difference between both J_s and q_s values recommended by Hannigan et al. [6] given in Table 1 and those proposed by the authors given in Table 7. To simplify the comparison, both J_s and q_s values are calculated using the weighted average SPT *N*-values given in Table 8. Fig. 10 shows that the percent improvement in *MQ* for the EOD condition increases with a larger difference in the dynamic soil parameters. This observation was noted in Table 8 with no or little improvement in *MQ* for ISU3 and ISU4, because the differences in the shaft parameters (J_s and q_s) as shown in Figs. 4 and 5, respectively, for average SPT *N*-values between 8 and 10 are not significant. A similar conclusion cannot be made for the BOR condition due to limited available data. The improvement in matching the measured and computed pile responses confirms the suitability of the improved signal matching technique used in quantifying the dynamic soil parameters.

To validate the empirical equations developed for shaft dynamic soil parameters for cohesive and cohesionless soils as summarized in Table 7, data from an independent test pile, ISU8, which

Table 9
Summary of soil properties, soil resistances, and estimated dynamic soil parameters for ISU8.

Test pile	Depth below ground (m)	Soil type-USCS	Ave. CPT unit tip resistance, q_c (kPa)	Ave. CPT unit skin friction, f_s (kPa)	Ave. friction ratio, *FR* (%)	Ave. SPT *N*-value	Est. and adjusted soil resistance at EOD, R_s (kN)	Damping factor at EOD, *J* (s/m)	Quake value at EOD, *q* (mm)
ISU8	0.40	CL	1195	57	4.37	5	6	0.11	4.79
	1.58		967	63	6.66	5	23	0.11	4.79
	2.74		1887	97	5.28	6	23	0.13	4.20
	3.90		1340	77	5.92	5	21	0.11	4.79
	5.09		1059	41	4.02	4	20	0.08	5.45
	6.25		1125	44	3.88	5	20	0.11	4.79
	7.41		846	29	3.28	2	16	0.04	7.07
	8.60		3342	29	1.13	2	22	0.04	7.07
	9.75	SW	4977	29	0.57	2	31	0.54	14.30
	10.91		21,257	133	0.65	2	163	0.54	14.30
	12.10	CL	11,650	89	1.64	11	96	0.27	2.19
	13.26		4000	74	2.28	11	26	0.27	2.19
	14.42		3971	78	2.38	10	26	0.24	2.50
	15.61		2789	68	2.59	17	23	0.46	1.01
	16.76		3655	154	3.93	24	23	0.69	0.40
	Toe	CL	3655	154	3.93	21	82	0.42	2.03

was not used in the aforementioned correlation studies, was used. Table 9 summarizes the measured soil properties and the estimated dynamic soil parameters. The total pile resistance of 621 kN at the EOD condition estimated using the routine CAPWAP matching technique was maintained, while the comparison was assessed in terms of *MQ*. While keeping the toe dynamic soil parameters closer to the values suggested by Smith [3] and Hannigan et al. [6], the application of the proposed empirical equations for shaft dynamic soil parameters has improved the *MQ* by 19%.

A comparison in terms of pile resistances was not evaluated, because (1) the static load tests were performed 9–36 days after EOD as shown in Table 3; (2) the effect of pile setup could have complicated the comparison for the EOD condition; (3) the goal of improving estimated pile resistance towards the SLT measured pile capacity will not validate the application of proposed empirical equations for dynamic soil parameters that represent the soil characteristics at the EOD condition; (4) the pile resistances at the EOD condition estimated from the routine CAPWAP approach as given in Table 4 have been accurately verified by extensive pile setup analyses [11]; and (5) the main objective of this paper focuses on improving the quantification of dynamic soil parameters, so that the dynamic soil characteristics can be realistically represented by a distribution of dynamic soil parameters instead of a constant value along an entire pile length, regardless of soil profile.

8. Conclusions

Although many researchers have urged the use of improved quality of soil parameters (i.e., damping factor and quake value) in dynamic analyses of pile foundations, this has not been achieved due to the lack of high quality field data and the indeterminate nature of the routine CAPWAP single matching technique. This paper, which proposes empirical equations for dynamic soil parameters based on an improved signal matching technique, draws the following conclusions:

1. Dynamic soil parameters are not constant along a pile depth, but do vary with different soil types and properties. For cohesive soils at EOD, the correlation studies revealed a direct relationship between the shaft damping factor and the SPT *N*-value and an inverse relationship between the shaft quake value and the SPT *N*-value.
2. For cohesionless soils at EOD, an inverse relationship between the shaft dynamic soil parameters and the SPT *N*-value was observed. Empirical equations were established to quantify these shaft dynamic soil parameters in terms of SPT *N*-value.
3. Pile setup increases the dynamic soil parameters for cohesive soils.
4. Correlation studies using CPT measured soil properties concluded that the shaft damping factor was influenced by different soil types. However, no clear relationship was observed between the shaft quake value and the CPT measured friction ratio.
5. The similar process of conducting the SPT and driving piles, in which both are subjected to a continuous impulsive hammer force, explains the more accurate correlation between dynamic soil parameters and SPT *N*-value.
6. The application of proposed empirical equations presents a distribution of realistic dynamic soil parameters along a pile length as well as improves the match quality. The application was verified using independent data obtained from test pile ISU8, resulting in a match quality improvement of up to 19%.
7. The percent improvement in match quality increases with the increase in the percent difference between the dynamic soil parameters recommended by Hannigan et al. [6] and those estimated using the proposed equations.

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