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Evaluation of Direct CPT Methods for Estimating the Ultimate Capacity of Driven Piles

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Abstract. The cone and piezocone penetration tests (CPT and CPTu) have been widely acknowledged as a useful in situ tests for subsurface investigation and soil characterization. The CPT is fast, robust, and economical test that can provide continuous soundings with depth. Due to similarity between pile and cone, the estimation of pile capacity from CPT data was among the earliest applications of the CPT. Accordingly, different direct Pile-CPT methods have been developed based on this analogy between the cone and the pile. Analyses and evaluation were conducted on eighty driven friction piles of different sizes and lengths that were failed during pile load tests. The Pile-CPT methods were used to estimate the load carrying capacities of the investigated piles (Q_p). The Davisson method was used to determine the measured load carrying capacities from pile load tests (Q_m). Four criteria were selected to evaluate the performance of the different Pile-CPT methods: the best fit line for Q_p versus Q_m, the arithmetic mean and standard deviation for the ratio Q_p/Q_m, the cumulative probability for Q_p/Q_m, and the histogram and log normal distribution for Q_p/Q_m. Results of the analyses have been used to evaluate the ability of different Pile-CPT methods for estimating the pile capacity. The results of this evaluation, the probabilistic, UF, and Philipponnat methods showed the best performance methods, followed by De Ruiter and LCPC methods, which were ranked next. The UWA and CPT2000 methods showed acceptable performance, too.

Keywords. Cone penetration test, Pile capacity, Driven piles, Statistical analysis, CPT classification.

1. Introduction

With the increase in traffic volume due to the rapid economic development, more and more bridges have been built across rivers and canals. Louisiana is not an exception to this role since it is developing of a rapid speed. The high percentage of wetlands, marshes, swamps, bayous, rivers, and lakes makes it necessary to construct pile supported structure in Louisiana. Most piles used for highway structures are driven precast prestressed concrete piles.

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The ultimate capacity of driven piles, which can be defined as the sum of soil resistance along the pile's side and the pile's tip resistance, can be estimated using pile load tests, dynamic analyses, Statnamic load tests, and static analysis based on soil properties from laboratory tests or in-situ tests. A number of static analysis methods were developed over the years to predict the pile capacity from in-situ tests such as cone penetration test (CPT).

The direct Pile-CPT methods are based on analogy between cone and pile. Many methods have been developed in recent years, which address different aspects of the pile-cone analogy. A description of Pile-CPT methods used in this research is available in literature such as [1, 2, 3, and 4].

Different researchers have studied the ability of Pile-CPT methods for estimating the pile capacity. Briaud and Tucker [5] evaluated the accuracy and precision of 6 different Pile-CPT methods using 98 pile load test database obtained from Mississippi State Highway Department. He stated that the accuracy of a Pile-CPT method is determined by means of Q_p/Q_m being close to 1, and the precision of a method refers to the scatter around the mean, quantified by standard deviation of Q_p/Q_m. He used the log-normal distribution of Q_p/Q_m for introducing a ranking index, RI, as follows:

$$RI = |\mu(a)| + \sigma(a) \tag{1}$$

where a is equal to $\ln(Q_p/Q_m)$ and μ and σ are mean and standard deviation, respectively. The advantage of using log-normal distribution is that the overprediction leads to lower RI value compared to under-predicting methods. The better performance of a method was defined by the lower value for RI which showed that LCPC method [6] was the best direct Pile-CPT method.

A research study by Abu-Farsakh and Titi [7] sponsored by Louisiana Department of Transportation and Development (LA DOTD) investigated eight different Pile-CPT methods. Four evaluation criteria for evaluating the prediction methods was adopted. The overall performance of the Pile-CPT methods was evaluated based on summing up the ranking of methods for the four different criteria. Based on this analysis, LCPC [6] and De Ruiter and Beringen [8] methods showed the best performances. This criterion was used by several researchers [i.e., 9, 10, and 11] for evaluating the different Pile-CPT methods. Hu et al. [12] used first-order second-moment (FOSM) resistance factor equation introduced by Paikowsky [13] with correction for coefficient of variation of load by Styler [14] in Load and Resistance factor Design (LRFD) equations for evaluating 14 different Pile-CPT prediction methods. Eq. (2) is obtained by substituting $\lambda_R = R_m/R_n$ in $\varphi = R_{design}/R_n$, where nominal resistance, R_n equals to side resistance plus 1/3 of the tip resistance; measured resistance, R_m is the failure load, and R_{design}, is the predicted capacity of the corresponding Pile-CPT method.

$$R_{design} = \left({}^{\varphi}/_{\lambda_R}\right) R_m \tag{2}$$

The higher values for (φ/λ_R) the better the estimation method is. The study by on 21 piles in Florida and 28 from Louisiana by Bloomquist et al. [15] showed that LCPC [6] and Philipponnat [16] methods yield higher φ/λ_R values than the other Pile-CPT methods.

During the past two decades other CPT methods for estimating pile capacity have been developed. In order to take advantage of these new developments, it is necessary to evaluate the ability of these methods. In this research, 18 Pile-CPT methods were evaluated using a database of 80 pile load test cases with CPT tests performed within close proximity in Louisiana. Soil type is one of the parameters which most of the methods estimations are dependent on it. In this research, probabilistic estimation [17] and Robertson [18] CPT soil classification methods have been used for determining the soil type. Based on CPT data, probabilistic method determines the probability of soil behavior (clay, sand, and silt), while Robertson [18] method presents a chart dividing the soil behavior into 9 different soil types. Comparison between pile capacity values obtained using each of these two soil classification methods was discussed. For this purpose, statistical analysis was used to examine if there was a significant difference using any of these soil classification methods for each Pile-CPT method. The evaluation criteria used by Abu-Farsakh and Titi [7] were used here to evaluate the performance of 18 Pile-CPT methods.

2. Research Methodology

2.1. Characteristics of the investigated piles

Results from 80 PPC piles in Louisiana have been used to assess the ability of different Pile-CPT methods to predict the pile capacity. The information of the piles such as pile length, pile diameter, CPT tests, and static load tests have been collected from Louisiana Department of Transportation and Development (LA DOTD). The piles' lengths range from about 11 to 61 m (35-200 ft.) and the diameters range from about 356 mm to 914 mm (14-36 inch). In addition, boring data near to the pile locations has been used in DRIVEN software (using α and Nordlund methods for clays and sands, respectively) which shows that most of the pile capacity driven in Louisiana soil is due to side resistance. Only four piles had a tip resistance more than 50% of the total pile capacity. The proportion of pile capacity in clay layers to the total pile capacity (defined as clay contribution) has been used to characterize the dominant soil for the pile database. Based on this analysis, piles were driven into different sandy, clayey, and layered soils.

2.2. Axial pile capacity from static load tests

Quick Load Test procedure as described in ASTM D1143 [19] were performed on different piles after 14 days of driving to obtain the load-settlement curve. The ultimate load capacity of the piles was determined based on the Davisson method [20]. Davisson failure criterion defines pile capacity as the load causes the pile top deflection equal to the calculated elastic compression plus 3.8 mm (0.15 inch) plus 1/120 of the pile's width/diameter. For piles with diameters more than 610 mm (24 inch), based on Florida Department of Transportation FDOT 2010 specification [21], section 455 the criterion is modified to calculated elastic compression plus 1/30 of the pile's width/diameter.

2.3. Estimating pile capacity, Q_p for Pile-CPT methods

In order to use CPT for calculating, adjacent CPT soundings have been used. For improving the quality of CPT results, the cone resistance should be corrected due to the pore pressure acting behind the cone shoulder [22], using the Eq. (3):

$$q_t = q_c + (1 - a)u_2 \tag{3}$$

where a is the net area ratio for the cone (0.59 for CPT used in this research). For most of the cases (68 piles), no measured pore pressure, u_2 were available. A comparison between CPT and CPTu results conducted in different locations in Louisiana, led to obtain a corrected factor dependent on the measured cone resistance and its depth, as described below:

- If $q_c < 1\ MPa$: $q_t/q_c = \min(1 + 0.2 \times depth/30\,, 1.2)$
- If $1 < q_c < 2.5\ MPa$, $q_t/q_c = \min(1 + 0.15 \times (depth - 6)/37\,, 1.15)$
- If $2.5 < q_c < 5\ MPa$, $q_t/q_c = \min(1 + 0.1 \times (depth - 6)/37\,, 1.1)$
- If $q_c > 5\ MPa$, $q_t/q_c = 1$

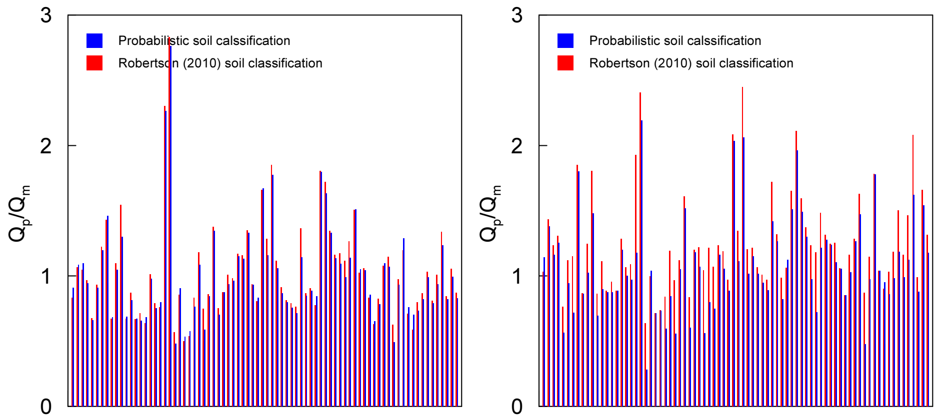
where depth is measured depth in meters of the q_c data.

The investigated eighteen (18) Pile-CPT methods include: LCPC [6], Schmertmann [23], De Ruiter and Beringen [8], Philipponnat [16], UF [12], probabilistic [24], Aoki [25], Penpile [26], NGI [*27*], ICP [28], UWA [29, 30], CPT2000 [31], Fugro [32, 33], Purdue [34], Tumay and Fakhroo [35], Aoki and De Alencar [36], and Togliani [37] and Zhou [38]. All of these methods depend on soil type, pile type and pile installation method. Therefore, in order to use the CPT for calculating the pile capacity, it is necessary to classify the soil. In this study, the Probabilistic estimation [17] and Robertson [18] CPT classification methods were implemented in a Visual Basic computer code and used for soil classification and determining the soil type with depth.

3. Results and Discussion

3.1. Sensitivity of Pile-CPT methods to the soil classification method

For each method the value of Q_p/Q_m has been obtained using probabilistic estimation [17] and Robertson [18] CPT soil classification methods. As an example, the results for Philipponnat and UWA methods are shown in Figure 1.



(a) Philipponnat method (b) UWA method

Figure 1. Value of Q_p/Q_m using probabilistic vs Robertson (2010) soil classifications.

As seen in Figure 1(a), the value of (Q_p/Q_m) for Philipponnat method is not much different for probabilistic estimation and Robertson CPT soil classifications. On the other hand, the difference between these proportions is significant in UWA method. For quantifying this difference, the value of diff is defined in Eq. (4), which represents the percentage of increase in Q_p/Q_m in case of using probabilistic soil classification compared to Robertson soil classification for each method.

$$\text{diff (\%)} = \left[(Q_p/Q_m)_{\text{probabilistic}} - (Q_p/Q_m)_{\text{Robertson}}\right] \times 100 \tag{4}$$

Statistical analysis (using SAS/STAT™ software) has been used to test the null hypothesis of diff (%) equal to zero for different methods. The null hypothesis is rejected in all the methods (other than LCPC, Schmertmann, and Aoki) which means that the soil classification has a significant effect on the ability of the methods for estimating the pile capacity. The statistical results for diff (%) is described in Table 1.

Table 1. Mean, standard deviation, max and min values of diff (%) for different CPT methods.

CPT methods		LCPC	Schmertmann	De Ruiter	Philipponnat	UF	Probabilistic	Aoki
diff (%)	mean	-1.24	-0.18	-4.63	-2.97	-3.02	1.38	-1.69
	SD	9.03	1.91	7.68	6.21	10.00	3.52	9.31
	max	27.54	3.12	14.01	11.57	24.72	13.65	21.81
	min	-24.50	-8.78	-33.17	-24.49	-31.68	-13.27	-27.35

CPT methods		Penpile	NGI	ICP	UWA	CPT2000	Fugro	Purdue
diff (%)	mean	-0.82	-8.73	-9.03	-15.85	-10.47	-6.44	-8.43
	SD	1.74	10.09	9.04	15.44	10.57	11.31	11.59
	max	3.33	11.83	5.12	10.97	6.03	40.57	33.41
	min	-8.32	-47.88	-38.39	-75.05	-38.12	-30.52	-32.56

The lowest mean values of diff (%) are for Schmertmann and Penpile methods, which shows that on average these methods are less dependent on the soil classification method. On the other hand, UWA, CPT2000, ICP, NGI and Purdue methods show the highest mean value for diff (%), which implies that these methods show more significant difference for pile capacity dependent on the kind of soil classification used for them.

Analysis of standard deviations for the above methods shows that Penpile, Schmertmann, and probabilistic methods have the lowest values which implies that these methods sensitivity to the soil classification method is low. On the other hand, UWA, Purdue, Fugro, NGI and CPT2000 methods have higher values for standard deviation and therefore their sensitivity to the soil classification method is higher.

The max and min values of diff (%) in Table 1 represent the range of diff (%). The lowest range is for Penpile, probabilistic, and Schmertmann methods, which is around$\pm$10%. UWA method have the highest range of -75% to +10%, which means that using probabilistic soil classification might estimate percentage of pile capacities 75% less or 10% more than using Robertson soil classification. The range of diff (%) for other methods are about -40% to +30%.

It should be noticed that the value of diff is dependent on the way of implementing soil classification methods for each method. For the rest of this study, the average values of Q_p from probabilistic estimation and Robertson soil classifications have been used to evaluate the ability of methods for estimating the pile capacity.

3.2. Evaluation of Pile-CPT methods

Four different criteria were used to evaluate the ability of each Pile-CPT method to predict the axial capacity of the piles:

- The equation of best-fit line of estimated versus measured pile capacity with the corresponding coefficient of determination: Linear regression is used to find a straight line between Q_m as the x values and Q_p as the y values. Forcing the regression line to pass through the origin, leads to linear regression without the intercept term, $y = \beta x$, where the slope of best-fit line, β is found by the least-square approach in Eq. (5).

$$\beta = \frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} {x_i}^2} = \frac{\overline{xy}}{x^2} \tag{5}$$

  Coefficient of determination, R^2 is the proportion of the variance in the dependent variable, y from the independent variable, x. Eq. (6) shows the most general definition of R^2.

$$\mathrm{R}^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y}_i)^2} \tag{6}$$

  where $\hat{y}$ is the predicted values by the regression model and $\bar{y}$ is the mean of observed data (Q_p). R^2 ranges from 0 to 1 and shows how well Q_p values are replicated by the model. Accuracy and precision of a method can be estimated by having β and R^2 values close to 1, respectively.

- The arithmetic mean, μ and standard deviation, σ for Q_p/Q_m: Mean and standard deviation are basic measures for accuracy and precision of CPT methods for predicting the pile capacity. Standard deviation should be understood in the context of the mean of data. Coefficient of variation, CV is defined as the ratio of the standard deviation to mean and shows the extent of variation in relation to mean.

- The 50 and 90% cumulative probabilities of Q_p/Q_m: The concept is to arrange Q_p/Q_m values for each method in an ascending order and estimate the cumulative probability (P) from Eq. (7) [39].

$$\mathrm{P} = \frac{i}{(n+1)} \tag{7}$$

The 50 and 90% cumulative probabilities are calculated as P_{50} and P_{90}, which provide an additional evaluation criteria to estimate the ability of Pile-CPT methods for predicting the axial capacity of piles. It should be noticed that P_{50} and P_{90} are representatives of median and 90 percentile of values of Q_p/Q_m, respectively. P_{50} values closer to 1 with a lower range of $P_{90} - P_{50}$ represent the best method.

- The 20% accuracy level for Q_p/Q_m obtained from histogram and log-normal distribution: The value of Q_p/Q_m theoretically ranges between zero to infinity, with an ultimate value of 1. Therefore, log-normal distribution is better to catch the properties of Q_p/Q_m than normal distribution. The log-normal density is defined in Eq. (8).

$$\mathrm{f(x)} = \frac{1}{\sqrt{2\pi}\,\sigma_{ln}\,x}\exp\left[-\frac{1}{2}\left(\frac{\ln(x)-\mu_{ln}}{\sigma_{ln}}\right)^2\right] \tag{8}$$

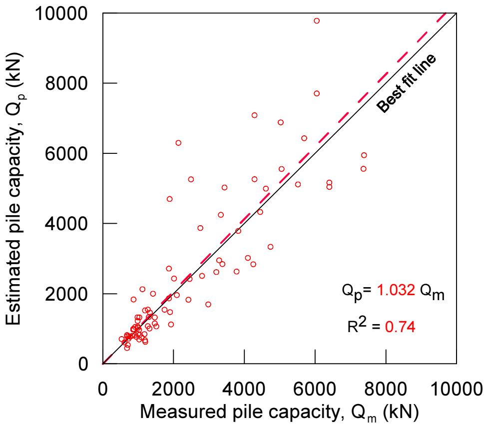
where $x = Q_p/Q_m$, μ_{ln} and σ_{ln} are mean and standard deviation of $\ln(Q_p/Q_m)$, respectively. The histogram and log-normal distributions are used to calculate the ability of CPT methods to predict the pile capacity within a specified accuracy level. In this research 20% accuracy has been chosen, which is the likelihood for Q_p values within 0.8 to $1.2Q_m$.

Figure 2 shows how these criteria were calculated for LCPC method. The line of best fit obtained by regression analysis, shown in Figure 2 (a) is used to calculate the value of $\beta = Q_{fit}/Q_m$ and coefficient of determination, R^2. Figure 2 (b) shows the values of Q_p/Q_m for 80 piles. The arithmetic mean and standard deviation was calculated and used as the second criterion. The third evaluation criterion based on 50 and 90% cumulative probability is shown in Figure 2 (c). Histogram and log-normal distribution for LCPC method is shown in in Figure 2 (d). The area under log-normal curve and the actual values of Q_p/Q_m were used to calculate the probability of predicting the pile capacity within 20% accuracy, as the fourth criterion.

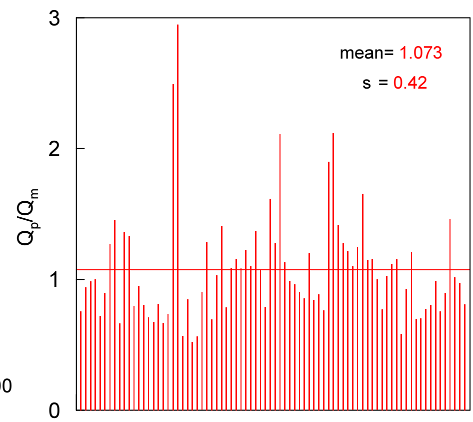
The same procedure as shown in Figure 2 has been done to calculate all 4 criteria for each method. Table 2 shows the results of each method based on these criteria. The overall performance of the Pile-CPT methods was evaluated using the Ranking Index, RI, which is the summation of ranking of each method in each criterion. The RI values calculated for each method are shown in Table 2, which was used to find the final ranking of the methods.

Based on the results of this analysis, Probabilistic, UF, and Philipponnat methods show the best performance. These methods have the same approach. Basically, the UF and probabilistic methods are the advanced form of the Philipponnat method. De Ruiter and LCPC methods were ranked nest. UWA and CPT2000 methods are the next best methods on the ranking. It should be noticed that CPT2000 has the same approach as UWA, however the formula is simpler and less assumptions are used in it.

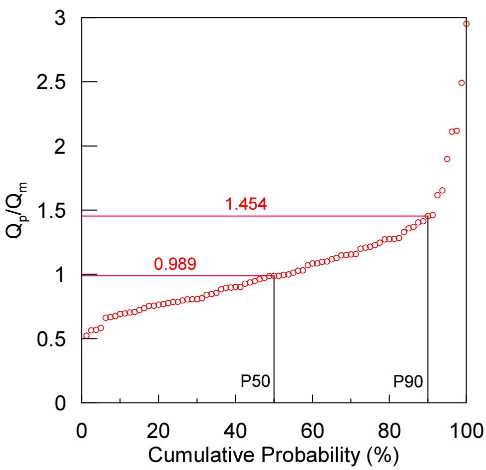
The results of the study are consistent with studies performed by Briaud and Tucker [5], Abu-Farsakh, M. Y., and Titi [7], and Hu et al. [12] who showed that LCPC, De Ruiter and Philipponnat methods show acceptable performance among all Pile-CPT methods.



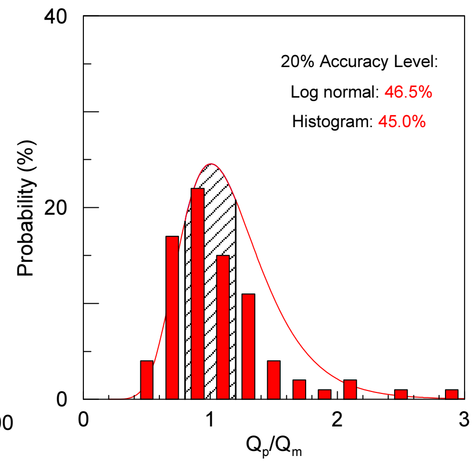
(a) Best fit-line



(b) Arithmetic mean and standard deviation



(c) cumulative probability of P_{50} and P_{90}



(d) Histogram and Log-normal distribution

Figure 2. Evaluation of LCPC method using the criteria.

Table 2. Ranking of Pile-CPT methods based on criteria used in this study.

	Best fit calculation			Arithmetic calculations of			Cumulative probability			±20% Accuracy (%)			Overall rank	
Pile capacity method	Q_{fit}/Q_m	R^2	R1	Mean	σ	R2	Q_p/Q_m at P_{50}	Q_p/Q_m at P_{90}	R3	Histogram	Log-normal	R4	RI	Final rank
Probabilistic	0.97	0.78	3	1.03	0.33	1	0.99	1.42	1	56.25	48.58	2	7	1
De Ruiter	0.98	0.77	4	0.95	0.34	2	0.87	1.24	2	53.75	48.35	3	11	2
UF	1.03	0.82	1	1.04	0.36	4	0.95	1.45	8	57.5	51.61	1	14	3
Philipponnat	1.03	0.79	2	1.02	0.38	5	0.93	1.42	6	50	48.27	5	18	4
LCPC	1.03	0.74	5	1.07	0.42	8	0.99	1.45	4	45	46.47	6	23	5
UWA	1.19	0.82	6	1.17	0.36	9	1.09	1.60	10	53.75	47.39	4	29	6
CPT2000	1.17	0.79	9	1.11	0.38	7	1.08	1.56	7	42.5	45.59	7	30	7
Price and Wardle	0.84	0.79	8	0.83	0.28	3	0.78	1.21	9	33.75	37.10	13	33	8
Schmertmann	1.20	0.77	10	1.21	0.43	11	1.18	1.58	5	42.5	43.38	8	34	9
Penpile	0.54	0.85	15	0.59	0.16	6	0.57	0.77	3	8.75	11.52	21	45	10
NGI05	1.28	0.72	13	1.24	0.56	14	1.10	1.96	15	42.5	36.79	10	52	11
Aoki	0.83	0.64	12	0.77	0.39	10	0.65	1.27	11	13.75	27.81	19	52	11
Tumay Fakhroo	1.29	0.69	14	1.36	0.47	13	1.26	2.02	14	36.25	35.20	12	53	13
Fugro	1.44	0.75	17	1.34	0.61	17	1.15	2.14	18	45	33.80	11	63	14
ICP	1.49	0.74	18	1.33	0.60	16	1.22	2.12	17	30	33.46	14	65	15
Purdue	1.45	0.60	19	1.29	0.72	19	1.02	2.36	20	50	33.59	9	67	16
Zhou	1.49	0.85	16	1.68	0.47	18	1.60	2.20	16	15	13.99	20	70	17
Togliani	1.70	0.81	20	1.83	0.54	20	1.79	2.45	19	10	9.23	22	81	18

4. Conclusions

Eighteen (18) direct Pile-CPT methods for estimating the ultimate capacity of piles were evaluated in this study using 80 friction piles driven in Louisiana. The measured pile capacity, Q_m was calculated for each pile from load-settlement curve.

Statistical analysis showed that there is a significant difference between estimated pile capacities obtained using each soil classification method. The value of diff (%) was defined as the difference between percentages of estimated to measured pile capacity for probabilistic and Robertson (2010) soil classifications. Schmertmann and Penpile methods showed lower mean and standard deviation for diff (%), which implies that these methods are less sensitive to the kind of soil classification used for determining the soil type. The max and min values of diff (%) showed a range of about 10% for these methods. On the other hand, UWA method had the highest value for mean and standard deviation for diff (%), which implies that this method has the highest sensitivity to the soil classification method. The range of diff (%) for UWA method is -75% to +10%, which proves that estimating the pile capacity from this method is completely dependent on the soil classification method used for determining the soil type. Based on these results, it can be suggested that for sensitive methods like UWA method, the average of estimated pile capacity using probabilistic estimation and Robertson soil classification should be used. On the other hand, using either soil classifications for some methods such as Schmertmann and Penpile methods changes the estimated pile capacity for about 10% of the measured pile capacity and therefore choosing either soil classification methods for determining the soil type is not a critical issue for them.

Four different criteria (Best fit line, Arithmetic mean and standard deviation, Cumulative probability, and Histogram and Log-normal distributions) were used to evaluate the performance of the Pile-CPT methods. Probabilistic, UF, and Philipponnat methods, which have the same approach for estimating the pile capacity, showed the best performance. De Ruiter LCPC were ranked next. The UWA and CPT2000 methods showed acceptable performance, too. Based on this research, we conclude that Pile-CPT methods are able to estimate the ultimate pile capacity with acceptable accuracy.

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