Ain Shams Engineering Journal (2016) 7, 885–893

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
www.sciencedirect.com

CIVIL ENGINEERING

Reliability and construction control of vibro piles

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Received 27 August 2015; revised 15 November 2015; accepted 28 December 2015
Available online 15 February 2016

KEYWORDS

LRFD;
Driven piles;
Static methods;
Dynamic formulas;
Construction control

Abstract The goal of this study was to determine the most reliable and efficient combination of design and construction methods required for vibro piles. For a wide range of static and dynamic formulas, the reliability-based resistance factors were calculated using EGYPT database, which houses load test results for 318 piles. The analysis was extended to introduce a construction control factor that determines the variation between the pile nominal capacities calculated using static versus dynamic formulae. From the major outcomes, the lowest coefficient of variation is associated with Davisson's criterion, and the resistance factors calculated for the AASHTO method are relatively high compared with other methods. Additionally, the CPT-Nottingham and Schmertmann method provided the most economic design. Recommendations related to a pile construction control factor were also presented, and it was found that utilizing the factor can significantly reduce variations between calculated and actual capacities.

1. Introduction

Large diameter cast in-situ concrete bored piles (or drilled shafts) are the most commonly used type of bridge foundations [1]. Although prefabricated driven piles are more cost effective compared to bored piles, driven piles are not preferred for high-volume bridges due to their construction control requirements and environmental restrictions [2]. According to El-Kasaby [3], vibro piles (a type of cast in-situ driven pile) are still being used in Egypt for low-volume bridges and remote structures that are located out of metropolitan areas. A vibro pile is formed in the ground by installing a steel casing with a base plate to the desired depth, after that a steel reinforcement cage is inserted inside the casing followed by concrete casting. The steel casing is then removed to be used for installing other piles. The current regional practice of estimating the design capacity of vibro piles is primarily based on static analysis methods, while the construction control aspects are addressed via applying dynamic formulas.

For a selected static method or dynamic formula, the pile design may be generally achieved using the Working Stress Design (WSD) approach, Limit State Design (LSD) or the Load and Resistance Factor Design (LRFD) approaches. Until now, the regional practice is still based on the Factor

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Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2015.12.009
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Nomenclature

c	soil cohesion
C_a	soil adhesion
f_c	cone sleeve friction
K_H	coefficient of the lateral earth pressure
K_{sx}	mean bias ratio between the measured and calculated resistances
L	pile embedded length
N	sample size
N_c	end-bearing capacity factor in cohesive soil
N_q	end-bearing capacity factor in cohesionless soil
p_b	effective vertical stress at the pile tip
p_f	probability of failure
p_o	effective vertical stress
Q	structural loads
Q_b	ultimate end-bearing capacity
q_c	average cone tip resistance
Q_{nom}	nominal pile capacity
Q_s	ultimate skin friction capacity
Q_{ult}	ultimate total pile capacity
R	pile radius
α	ratio between pile to cone sleeve diameters
β^*	skin-friction reduction coefficient
β	reliability index
γ	load factor
δ	soil–pile friction angle
ΔL	thickness of soil layer
λ	mean bias
ξ_{cc}	construction control factor
σ	standard deviation
φ/λ	efficiency factor
φ	resistance factor
ϕ	soil angle of internal friction

of Safety (FS) associated with the WSD, which is subjective and cannot insure reliable, consistent, and sustainable performance of substructures [4–6]. This drawback of the WSD stems from ignoring various sources and levels of uncertainties related to loads and capacities of deep foundations, causing conservative FS to be used [7].

To achieve sustainable designs of deep foundations, there was a progressive transition over the past few decades to utilize reliability-based approaches. Therefore significant efforts have been directed toward the development and application of the LRFD in geotechnical design standards such as European Standard (EN), American Association of State Highway and Transportation Officials (AASHTO) and other international codes. At present, the Egyptian code (which serves as bases for the unified regional code) is being updated to include the LRFD approach for deep foundations. The main reason for this update is twofold; first to follow the international trend of adapting reliable and sustainable designs of deep foundations; and second to integrate construction control aspects in the design process and encourage the use of driven piles.

In this study, the LRFD calibration framework included five static methods and one dynamic formula. The criterion was to provide design recommendations that cover the wide range of methods available in design specifications such as AASHTO, Canadian Design Manual, and Egyptian Code for Deep Foundations (ECDF). Moreover, the calibration framework was based on using four different pile ultimate capacity determination criteria from the Static Load Test (SLT) results. These criteria were Davisson [8]; Chin [9]; Modified Chin [10]; and Brinch Hansen [11]. After developing the LRFD resistance factors, the most efficient static method was compared with the factored capacity acquired from the Hiley dynamic formula [12]. This was done in an attempt to define the difference between static and dynamic outcomes, hence provide an embedded construction control term that can be applied to static methods – a procedure that can reduce the gap between the design and construction stages.

2. Static analysis methods

Static analysis methods are used to estimate the number and length of piles required to release the bidding and contracting documents during the initial design stage. Selecting the most appropriate static method requires sufficient knowledge of the site subsurface conditions and the design method implications on a specific type of pile. Internationally, the updated interim of the AASHTO specifications [13] uses combinations of static methods for driven piles in sand, clay and mixed soils. In this study, the AASHTO pile design combination that is based on α-Tomlinson and SPT-Meyerhof for cohesive and cohesionless soils, respectively, was included in the calibration framework – this combination was indicated as the "2007 AASHTO" method. Additionally, the method by Nottingham and Schmertmann [14] that is based on the Cone Penetration Test (CPT) results was included herein and indicated as the "CPT N&S" method.

In addition, three regional methods were considered in this study: two from the current Egyptian code [10] and one adapted from the Canadian foundation manual [15]. These methods were, respectively, indicated as the "2001 ECDF" method, the "2001 CPT" and the "2014 ECDF" methods. Since these three methods are not recognized internationally, a brief description for each of them is provided.

2.1. The 2001 ECDF method

The 2001 ECDF method was modified after Tomlinson in cohesive [16] and Nordlund in cohesionless [17] soils, respectively. In this method, the total ultimate pile capacity, Q_{ult}, is the summation of the ultimate skin friction capacity, Q_s, and the ultimate end-bearing capacity, Q_b. In cohesive material, the Q_{ult} of driven piles can be calculated using Eq. (1).

$$Q_{ult} = C_a 2\pi RL + cN_c\pi R^2 \tag{1}$$

where C_a represents the soil adhesion along the pile length (from Table 1); R, the pile radius; L, the pile embedded length;

Table 1 Cohesion and adhesion values used for the 2001 ECDF method in cohesive soil.

Pile type	Soil index	Soil cohesion, c (kPa)	Soil adhesion, C_a (kPa)
Concrete and timber piles	Very soft	0–12.5	0–12.5
	Soft	12.5–25	12.5–24
	Medium	25–50	24–37.5
	Stiff	50–100	37.5–47.5
	Very stiff	100–200	47.5–65
Steel piles	Very soft	0–12.5	0–12.5
	Soft	12.5–25	12.5–23
	Medium	25–50	23–35
	Stiff	50–100	35–36
	Very stiff	100–200	36–37.5

c, the average cohesion of soil along a distance equal to $1.5R$ above and below the pile tip; and N_c, the end-bearing capacity factor (typically equal to 9.0). In cohesionless material, the Q_{ult} can be calculated using Eq. (2).

$$Q_{ult} = \sum_{0}^{L} K_H p_o tan\,\delta \cdot 2\pi R \Delta L + p_b N_q \pi R^2 \tag{2}$$

where K_H represents the coefficient of the lateral earth pressure acting along the pile length (from Table 2); p_o, the effective vertical stress along the pile length; δ, the soil–pile friction angle (δ equal to 20° for steel piles; 3/4 ϕ for concrete and timber piles; and ϕ is the soil angle of internal friction); ΔL, the soil layer thickness; p_b, the effective vertical stress at the pile tip; and N_q, the end-bearing capacity factor (from Table 3).

2.2. The 2001 CPT method

The 2001 Egyptian code also provides a pile design method that is considered as a simplified version of the CPT-Nottingham and Schmertmann [14]. This method is the 2001 CPT, in which the total ultimate load can be calculated in kilo Newtons using Eq. (3).

$$Q_{ult} = \alpha q_c(\pi R^2) + f_c(2\pi RL) \tag{3}$$

where α is the ratio of the pile to the cone sleeve diameters (typically assumed equal to 0.7); q_c, the average cone tip resistance along a length of 6D above and 3D below the pile tip ($q_c \leqslant 15$ MPa); and f_c, the average cone sleeve friction along the pile length ($f_c \leqslant 100$ kPa). In case if f_c is not available, it can be estimated as $f_c = 0.005\ q_c$.

Table 2 Values of K_H coefficient under compression and tension loads.

Pile type	$K_{H\ (Compression)}$	$K_{H\ (Tension)}$
H-pile	0.5–1.0	0.3–0.5
Displacement pile	1.0–1.5	0.6–1.0
Displacement tapered pile	1.5–2.0	1.0–1.3
Displacement screw pile	0.4–0.9	0.3–0.6
Driven pipe piles with $D < 60$ cm[a]	0.7–1.5	0.4–1.0

[a] D is the pile diameter.

Table 3 The N_q values used for the 2001 ECDF method in cohesionless soil.

$\phi^{\dagger}$ (°)[a]	25°	30°	35°	40°
N_q	15	30	75	150

[a] For displacement piles: $\phi^{\dagger} = (\phi + 40°)/2$. For non-displacement piles: $\phi^{\dagger} = \phi - 3°$.

2.3. The 2014 ECDF method

In the 2014 ECDF static method, the pile capacity in cohesive material is calculated similar to the 2001 ECDF method. The only difference is in capacity calculation in cohesionless material, which is based on recommendations from the Canadian Foundation Engineering Manual [15]. This implies the use of Eq. (4), where β^* is a skin-friction reduction coefficient and N_q is the end-bearing capacity factor (values for β^* and N_q are provided in Table 4).

$$Q_{ult} = p_b N_q \pi R^2 + \sum_{0}^{L} \beta^* p_o 2\pi R \Delta L \tag{4}$$

3. Development of LRFD procedures

As part of the ongoing research for the development of regionally calibrated LRFD resistance factors for the design of deep foundations, an electronic database (namely EGYptian Pile Test, or EGYPT) has been developed by AbdelSalam et al. [18] including information for 318 pile SLTs. From this database, the usable records for vibro piles available include 4 piles in sand, 12 in clay, and 24 in mixed soil profiles. Based on McVay et al. [19], the number of available records within each soil group is insufficient to run the required reliability analysis. Therefore, it was decided to use the Monte Carlo Simulation (MCS) for all the available records in the database to amplify the number of SLTs availability within these groups. Additionally, another group namely "*All piles*" was included in the analysis which consists of all the available records of vibro piles in the database. Adapting such *All piles* group is conventional because the database variations in terms of soil and pile conditions are very limited – as all the available vibro piles are concrete, the majority of them were driven in comparable geological formations, using the same driving hammer, and 92.5% of the them are end-bearing in a dense sand soil stratum located around 20 m from the ground surface.

Table 4 Values of β^* and N_q used for the 2014 ECDF method in cohesionless soil.

	Soil type	Displacement piles	Non-displacement piles
β^*	Silt	0.3–0.5	0.2–0.3
	Loose sand	0.3–0.8	0.2–0.4
	Medium sand	0.6–1.0	0.3–0.5
	Dense sand	0.8–1.2	0.4–0.6
	Gravel	0.8–1.5	0.4–0.7
N_q	Silt	20–40	10–30
	Loose sand	30–80	20–30
	Medium sand	50–120	30–60
	Dense sand	100–120	50–100
	Gravel	150–300	80–150

The LRFD resistance factors calibration was conducted for the previously selected design methods. Regarding the measured ultimate capacity (Q_{ult}) of the vibro piles, this was determined from the load–displacement curves of the SLTs based on Davisson, Chin, Modified Chin and Brinch Hansen criteria. Hence, the resistance factors were developed four times to cover each of the four criteria used to determine the measured Q_{ult} from SLT results. This was performed in order to provide recommendations needed for any possible combination and to arrive to the most efficient design scheme. In this paper, the focus was more on the results acquired for the *All piles* group based on Davisson's criterion, while the remaining outcomes are also summarized.

3.1. Calibration method

Based on recommendations by Paikowsky et al. [20] and AbdelSalam et al. [7], the First Order Second Moment (FOSM) is adequate for the reliability-based calibration of the LRFD resistance factors for pile foundations. Hence the FOSM equation was directly employed for the *All piles* group of the database. For the other groups (i.e., sand, clay, and mixed groups), the original mean-bias and standard deviation were calculated, then the values were entered into the Monte Carlo analysis. The original number of available data points in each group was significantly amplified after using a number of simulations equal to 50,000, while the output from the MCS was used as input for the FOSM equation to calculate the resistance factors.

Related to the reliability index (β) – which is an indication for the probability of failure – that is required in the calibration, Paikowsky et al. [20] recommended the use of $\beta = 2.33$ (probability of failure, $p_f = 1\%$) and 3.00 ($p_f = 0.1\%$) for redundant and non-redundant bridge pile foundations, respectively. In this study, a wider range of β values starting from 1.50 to 4.00 were used in order to provide more flexibility in the design depending on the type and importance of the structure. As for the Dead Load to Live Load (DL/LL) ratio, a DL/LL ratio of 2.0 was selected. However, it is worth noting that several researchers showed that the effect of changing the DL/LL ratio on the resistance factors is insignificant as per AbdelSalam et al. [7] and AbdelSalam and El-Naggar [6].

3.2. Goodness-of-fit

The distribution of each data set within the groups of vibro piles in EGYPT database (i.e., sand, clay, mixed and *All piles* groups) was represented by a probability density function (PDF) to determine the mean bias ratio between the measured and calculated resistances (K_{sx}). The best-fit for each PDF was checked for log-normality using two different statistical tests: the Anderson–Darling (AD) and the 95% Confidence Interval (95% CI) tests. In the AD test, an indication of the best-fit distribution type for a given data set is represented by the lower AD coefficient, while the p-value should be more than 0.005 in the 95% CI test (see [21] for more details on the statistical tests). As shown in Fig. 1, the AD and the 95% CI tests indicate that the lognormal distribution best-fits all the PDFs calculated for the six design methods based on Davisson criterion for the *All piles* group. Similar results were observed for other groups based on Chin, Modified Chin, and Brinch Hansen criteria. Therefore, all the vibro pile groups in EGYPT database best-fit the log-normal distribution and can be used in the FOSM analysis.

Fig. 2 shows the normal and lognormal frequency distributions for all the PDFs calculated for the six design methods based on Davisson's criterion for the *All piles* group. As seen from the lognormal distributions in the figure, the 2007 AASHTO method provides the closest conservative mean to unity, while the 2014 ECDF method provides the smallest standard deviation in comparison to other static methods. Also, it is noticed that the Hiley dynamic formula provides a reasonable mean and standard deviation, 0.66 and 0.39, respectively, compared to all static methods. For the normal distribution shown in Fig. 2, the ratio K_{sx} was negative in some cases, which is invalid and proves that assuming a normal distribution for loads and resistances is misleading.

Before conducting the LRFD calibration, the nominal performance of the six pile design methods was examined and compared with the measured nominal capacity from the SLT results based on Davisson's criterion. From the results, it was noticed that all the maximum, minimum, and average nominal capacities for all the available vibro piles in the database varied above and below the control value (which is Davisson's nominal capacity in this case), meaning that some

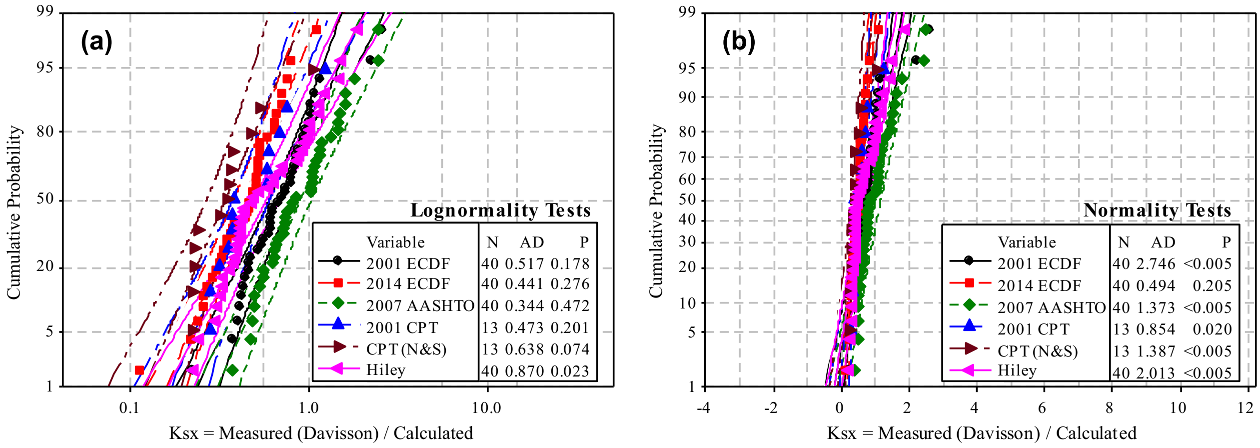

Figure 1 Goodness-of-fit of static methods in *All piles* group: (a) lognormal and (b) normal.

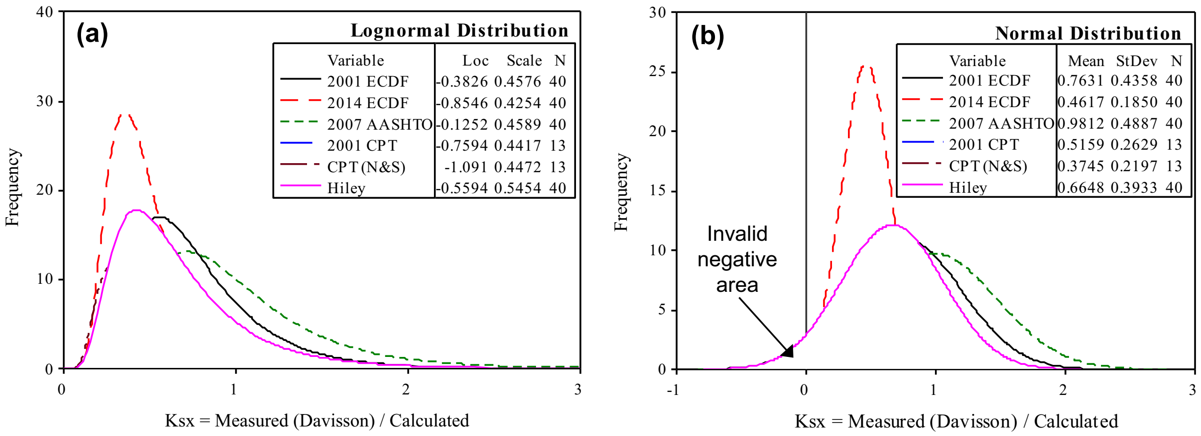

Figure 2 Distribution of static methods in *All piles* group: (a) lognormal and (b) normal.

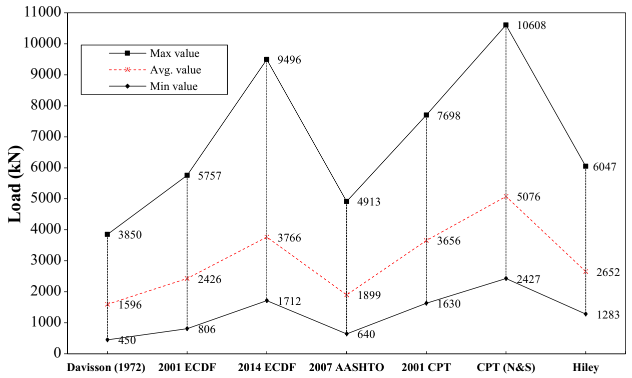

Figure 3 Full-range values for calculated vs. measured nominal capacities for the *All piles*.

methods are generally conservative while others are found to be unconservative. This is presented in Fig. 3, where all the static methods overestimated the pile nominal capacity and had a high mean bias.

3.3. Resistance factors

Table 5 represents the calibrated LRFD resistance factors (φ) for the *All piles* group using all the selected pile design methods with respect to the four chosen criteria of pile measured capacity determination. The table also includes the statistical parameters that were used in the analysis such as the sample size (N), mean bias (λ), standard deviation (σ), the coefficient of variation (COV), and the reliability index (β). For redundant pile groups, Table 5 summarizes the calibration based on Davisson, and the results show that the highest φ obtained was for 2001 ECDF, followed by the 2007 AASHTO and the 2014 ECDF methods, with φ values equal to 0.49, 0.40, and 0.30, respectively. For the calibration based on the Chin criterion, it was clear from Table 5 that the highest φ was for 2007 AASHTO with a value equals to 0.24, followed by the 2001 ECDF and the 2001 CPT methods, in that order, with φ values equal to 0.20 and 0.19, respectively. For the calibration based on Modified Chin, it was noticed from Table 5 that the resistance factors associated with Modified Chin are always lower than those associated with the original Chin criterion. Finally, the calibration based on Brinch Hansen generally provided slightly lower ϕ values compared with the other three criteria.

Therefore, the highest LRFD resistance factors acquired for the *All piles* group of EGYPT database were always associated with Davisson's criterion. However, it is very important to highlight the fact that higher resistance factors (ϕ) do not provide a true indication of the efficiency and economy of the design, as different static/dynamic methods lead to variable nominal pile capacities. In order to compare the efficiency of different methods relative to the actual pile behavior, the efficiency factors defined as φ/λ were calculated. The φ/λ factor ranges from 0 to 1.0, where higher φ/λ correlates to higher efficiency methods. In Table 5, the φ/λ factors are also represented. From the results it was found that, for the calibration based on Davisson's criterion, the 2001 ECDF method has the highest efficiency, followed by the CPT (N&S) and the 2014 ECDF methods. For calibration based on other criteria, the 2001 CPT and the CPT (N&S) methods always provided the highest efficiencies.

To summarize, the 2001 ECDF and the 2014 ECDF methods, in that order, have high ϕ and φ/λ factors and are suggested for vibro piles if CPT results are not available. If CPT results are available, the 2001 CPT and the CPT (N&S) methods are recommended because they consistently provide the highest efficiency in the design of vibro piles. Added to the previous, Davisson's criterion always yields the highest efficiency and the lowest COV, followed by Chin, Modified Chin, and then Brinch Hansen criteria.

A design chart was prepared to determine the resistance factors corresponding to different values of β (or probability of failure). As shown in Fig. 4a for *All piles* group (based on Davisson) φ decreases with increasing values of β. From this figure, a designer can find the appropriate φ for a given select β that reflects the pile redundancy, life time, structure importance, degree of quality control, and the extent of design conservatism. Also included in Fig. 4b is the φ/λ corresponding to different values of β for different static methods in *All piles* group. Two observations are apparent from Fig. 4 as follows: (1) the order of efficiency remains the same for different methods regardless of β; (2) the efficiency of the method decreases with increasing β; and (3) for non-redundant pile groups, it was found that the resistance factors were reduced by an average of 36% compared with redundant pile groups.

Table 5 Summary of the resistance factors for design methods in *All piles* group.

Q_{ult} from SLT	N	Static analysis method	Mean (λ)	St. dev. (σ)	COV	β = 2.33	
						ϕ[a]	ϕ/λ[b]
Davisson (1972)	40	2001 ECDF	0.79	0.18	0.23	0.49	0.62
	40	2014 ECDF	0.51	0.13	0.26	0.30	0.59
	40	2007 AASHTO	0.90	0.35	0.40	0.40	0.45
	13	2001 CPT	0.47	0.17	0.36	0.22	0.48
	13	CPT (N&S)	0.33	0.08	0.24	0.20	0.61
	40	Hiley	0.57	0.24	0.42	0.24	0.42
Chin Konder (1971)	40	2001 ECDF	0.68	0.40	0.59	0.20	0.30
	40	2014 ECDF	0.43	0.20	0.47	0.16	0.38
	40	2007 AASHTO	0.76	0.42	0.55	0.24	0.32
	13	2001 CPT	0.34	0.09	0.28	0.19	0.57
	13	CPT (N&S)	0.24	0.04	0.17	0.16	0.69
	40	Hiley	0.62	0.59	0.96	0.10	0.14
Modified Chin (2001)	40	2001 ECDF	0.54	0.48	0.89	0.10	0.16
	40	2014 ECDF	0.32	0.21	0.65	0.10	0.26
	40	2007 AASHTO	0.67	0.40	0.60	0.19	0.29
	13	2001 CPT	0.32	0.15	0.47	0.12	0.38
	13	CPT (N&S)	0.23	0.12	0.52	0.10	0.34
	40	Hiley	0.47	0.36	0.78	0.10	0.19
Brinch Hansen (1963)	40	2001 ECDF	0.89	0.63	0.70	0.20	0.23
	40	2014 ECDF	0.59	0.51	0.85	0.10	0.17
	40	2007 AASHTO	0.99	0.64	0.64	0.26	0.26
	13	2001 CPT	0.70	0.44	0.64	0.18	0.26
	13	CPT (N&S)	0.50	0.35	0.70	0.12	0.23
	40	Hiley	0.64	0.49	0.77	0.13	0.20

[a] LRFD resistance factor for vibro piles.
[b] Efficiency factor.

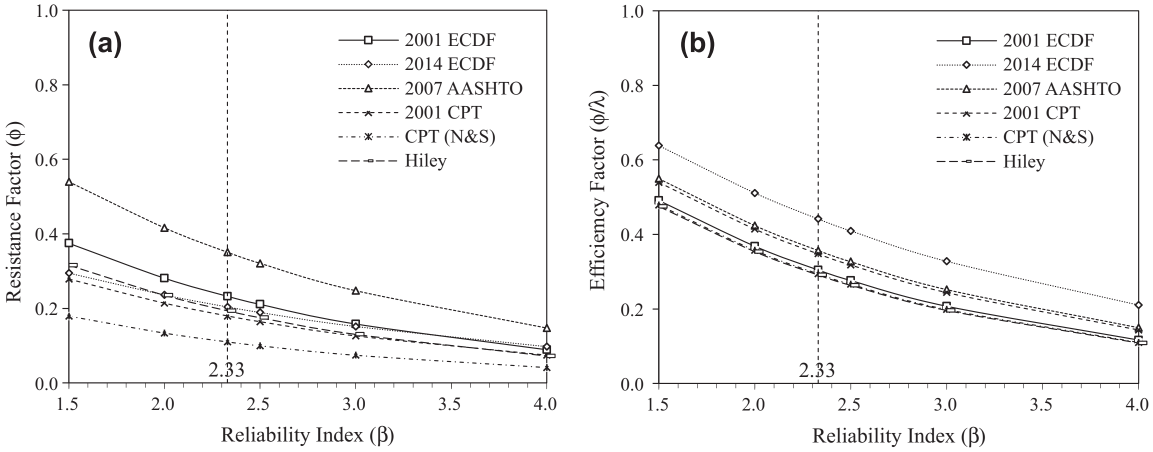

Figure 4 Charts for a range of β including: (a) resistance factors and (b) efficiency factors.

4. Construction control for driven piles

Construction control involves several measures in order to accurately verify the design capacity of vibro piles. The current local practice uses the 2001 ECDF method during the design stage, and uses the Hiley dynamic formula during the construction stage to confirm the designed capacity. If the desired pile capacity is not reached during construction, pile design and construction specifications must be adjusted accordingly by changing the number or dimensions of piles. This adjustment may result in significant alteration of the construction cost accompanied with major delays. To improve the accuracy of pile capacity determination and cost estimation during the design stage and to ensure the adequacy of pile performance, the construction control method using dynamic results can be integrated as part of the design procedures [22]. However,

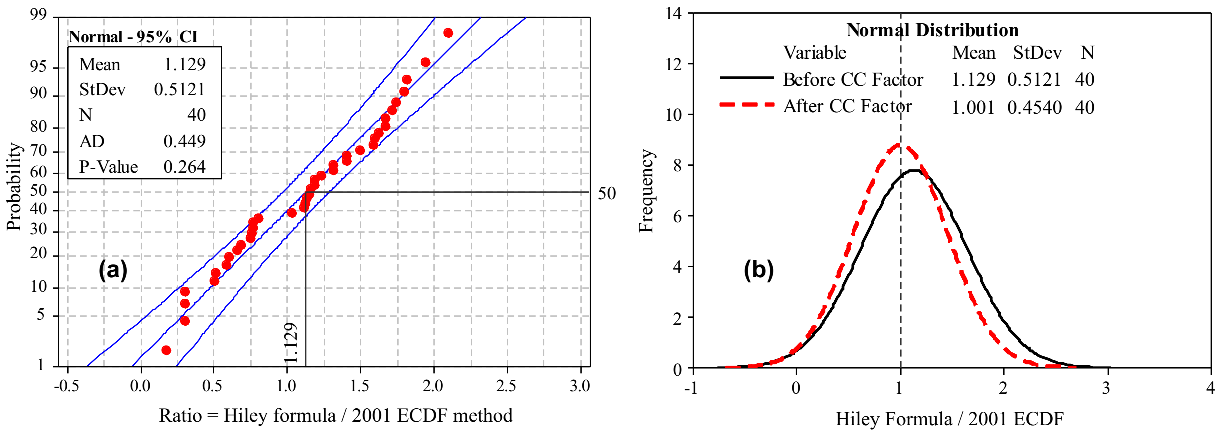

Figure 5 Construction control illustration (a) Hiley/2001 ECDF cumulative distribution and (b) PDFs before and after the ξ_{cc} application to 2001 ECDF factored capacity.

it is worth noting that basing the construction control on dynamic formulas is not the most accurate approach. In contrast, dynamic analysis methods that adapt the wave equation concept and depend on actual field measurements during pile driving are a more accurate compared to dynamic formulas.

The Hiley dynamic formula was selected in this study for construction control evaluation because it is most commonly used formula in the regional practice, it provided acceptable results as presented in previous sections of this paper, and also because there is no information available in EGYPT database about more accurate dynamic analyses methods such as wave equation or Pile Driving Analyzer (PDA). The proposed construction control evaluation approach depends on developing a Construction Control factor (ξ_{cc}) to adjust the pile design using a static method according to the Hiley formula results and according to recommendations by Roling et al. [22]. The ξ_{cc} should be multiplied by the originally developed LRFD resistance factors (φ) and the nominal capacity (R) calculated for a specific static design method (for example the 2001 ECDF method) as given in Eq. (5):

$$\gamma Q < \zeta_{cc}\varphi\, Q_{nom} \tag{5}$$

where γ is the structural load factor; Q, the structural load, ξ_{cc}, the proposed construction control factor, φ, the originally developed LRFD resistance factor for the 2001 ECDF method (see Table 5), and Q_{nom}, the nominal pile capacity estimated using the 2001 ECDF method.

Fig. 5a shows the cumulative probability distribution curves for the ratio of the factored pile capacity calculated using the Hiley formula to that calculated by the 2001 ECDF method for the *All piles* group based on Davisson's criterion. In the figure, the cumulative probability on the y-axis indicates the cumulative probability at which the factored pile capacity predicted by the Hiley formula is slightly higher than that predicted by the 2001 ECDF method. The cumulative probability was initially experimented at 25%, 50% and 75%, in an attempt to reach a mean bias closer to unity, and it was found that the probability of 50% provides the best results. Based on the theoretical normal distributions shown in the figure and the increased cumulative probability, the ratio of the Hiley formula and the 2001 ECDF method for the A*ll piles* group was determined to be 1.129 (which means that the $\xi_{cc} = 1.13$).

As illustrated in Fig. 5b, the ξ_{cc} was multiplied by the factored capacity (φ Q_{nom}) estimated using the 2001 ECDF method, which reduced the mean ratio between the Hiley formula and the 2001 ECDF method to unity. Also from the figure, it was noticed that the standard deviation was reduced from 0.51 to 0.45. Therefore, the application of the proposed construction control factor should guarantee matching the design capacity calculated using the 2001 ECDF method with the one calculated using the Hiley formula. Yet, it is important to highlight the fact that adapting the proposed construction control procedure should not alter the LRFD reliability index.

5. Summary and conclusions

This study aimed at establishing the LRFD design recommendations for vibro piles using information from 40 static load tests. Following the reliability-based calibration framework, the resistance factors were developed for five different static methods and one dynamic formula. These methods were the 2001 ECDF, the 2014 ECDF, the 2007 AASHTO, the 2001 CPT, the CPT N&S, and the Hiley formula. Additionally, the LRFD recommendations were developed to cover a wide range of pile ultimate capacity determination criteria such as Davisson, Chin, Modified Chin, and Brinch Hansen. To improve the accuracy of pile capacity determination and cost estimation during the design stage, a construction control factor (ξ_{cc}) was obtained and integrated as part of the design procedures. Summarized below are the major findings:

- Generally, the lowest coefficient of variation was always associated with Davisson's criterion, followed by Chin, Modified Chin, and Brinch Hansen, respectively.
- For Davisson-based LRFD calibration, the 2001 ECDF and the 2014 ECDF static methods, in that order, provided high resistance and efficiency factors. However, if CPT results are available, the 2001 CPT and the CPT (N&S) methods could even save more in the cost of vibro piles.

- It is recommended to include the 2014 ECDF method in the coming update for the Egyptian code of practice, also Davisson criterion is suggested for driven piles.
- The Hiley formula consistently provided a resistance factor of 0.24 corresponding to a relatively high efficiency of 0.42, which means that this formula is practically acceptable for vibro pile. However, it is highly recommended to use wave equation and PDA as a more accurate measure of the vibro pile capacity during driving.
- A construction control factor was successfully developed for the factored capacity of the 2001 ECDF method, which guarantees matching the results of the Hiley formula without altering the LRFD reliability index.
- Finally, comprehensive design charts based on a wide range of reliability indices were provided in this study to encourage the regional LRFD implementation for the design of vibro piles.

Acknowledgments

The study was conducted as part of an ongoing research to the development of the LRFD procedures for deep foundations in Egypt. The authors express gratitude for Consultant Eng. Mohamed Farid, and Eng. Ashraf Wahby, each of which provided essential support during the data collection process. Appreciation is also due to colleagues and students from the British University in Egypt (BUE) who helped in other processes.

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Dr. Baligh has been actively working with the student body of Helwan University since 1990. As university academic advisor, she organizes student training and field trips around Egypt and abroad and started the university's SIFE team, now called Enactus Helwan team. She is also faculty advisor for student MUNs (TEIMUN in The Hague, BIMUN in Bonn and AIMUN in Beijing). From 1996 to 2007, Dr. Baligh served as a board member on both the Students' Affairs Committee and the Environmental Affairs Committee at Helwan University's Faculty of Engineering.

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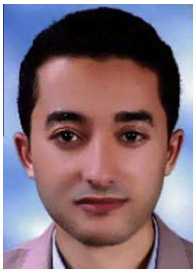
Dr. Baligh is active in the organization of international engineering conferences in Egypt. She served as a member of the organizing committees for the 11th African Regional Conference held in Cairo in 1996, the 1st and 2nd International Conferences on Civil Engineering held at Helwan University in 1998 and 2000, respectively, the 17th International Conference on Soil Mechanics and Geotechnical Engineering held in Alexandria in 2009, and as chairperson of the organizing committees of the 4th International Young Geotechnical Engineer's Conference (4iYGEC) in Alexandria in 2009 and the 3rd African Young Geotechnical Engineer's Conference (3AyGEC'12) in Cairo in 2012.



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