Article

Evaluation of the Static Design Procedure in the Canadian Foundation Engineering Manual for Piles in Cohesionless Soil

Hany El Naggar * and Islam Ezzeldin

Department of Civil and Resource Engineering, Dalhousie University, Halifax, NS B3H 4R2, Canada; is773306@dal.ca

* Correspondence: hany.elnaggar@dal.ca; Tel.: +1-902-494-3904

Abstract: Piles provide a convenient solution for heavy structures, where the foundation soil bearing capacity, or the tolerable settlement may be exceeded due to the applied loads. In cohesionless soils, the two frequently used pile installation methods are driving and drilling (or boring). This paper reviews the results of a large database of pile load tests of driven and drilled piles in cohesionless soils at various locations worldwide. The load test results are compared with the static analysis design method for single piles recommended in the Canadian Foundation Engineering Manual (CFEM) and other codes and standards such as the American Association of State Highway and Transportation Officials, Federal Highway Administration, American Petroleum Institute, Eurocode, and the Naval Facilities Engineering Command. An improved pile design procedure is proposed linking the pile design coefficients (β) and (N_f) to the friction angle of the soil, rather than employing the generalized soil type grouping scheme previously used in the CFEM. This improvement included in the new version of the CFEM 2021 produces a more unified value of the pile capacity calculated by different designers, reducing the obtained design capacity discrepancies.

Citation: El Naggar, H.; Ezzeldin, I. Evaluation of the Static Design Procedure in the Canadian Foundation Engineering Manual for Piles in Cohesionless Soil. *Geosciences* **2021**, *11*, 472. <https://doi.org/10.3390/geosciences11110472>

Academic Editors: Mohamed Shahin and Jesus Martinez-Frias

Received: 26 September 2021
Accepted: 11 November 2021
Published: 16 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: piles; pile design; pile capacity; friction angle; pile load tests

1. Introduction

The design of deep foundations is often based on a combination of experience and empiricism [1]. In recent decades, a gradual change in design methodology has developed from empirical models to a more theoretically based approach. Furthermore, advanced methods of pile analysis have been made possible by the availability of robust software programs [2]. The pile design process begins with the selection of an appropriate pile type, depending on the site, followed by an estimation of the interaction between the pile and the surrounding soil after installation [3]. The quality and capacity of deep foundations depend on factors such as the construction method, installation equipment, and workmanship. New methods are currently investigated for piling in cohesionless soil such as the sand compaction pile method (SCP) [4].

Deep foundations are generally used to transfer loads from superstructures to foundation soils in cases where the use of shallow foundations is not feasible. Besides, in some cases, piled rafts are used to withstand heavy loads from high rise buildings offering some advantages in terms of serviceability and efficient use of materials [5,6]. According to the load transfer mechanisms for vertical loading, two pile types can be identified: (a) End bearing piles, where the majority of the load is transferred via the pile tip by bearing; and (b) friction piles, where the majority of the load is transferred by friction throughout the pile length. It should be noticed that the uplift forces on the supporting piles should be considered when the structure is founded below the water table or due to the swelling impact of the surrounding soils [7]. Furthermore, in case of loose soil, the buckling impact should be investigated for end bearing piles under loading and unloading conditions [8]. To assess theoretical methods for calculating the ultimate capacity, full-scale load tests on random piles are recommended, especially for complex and large projects. The ultimate

pile capacity is usually defined as the point where the pile settlement increases rapidly under a sustained or slightly increased test load [9]. Thus, the actual capacity is determined by applying some criterion to the load-settlement data recorded in full-scale tests. Several reports present methods that can be used to evaluate the actual capacity of a single pile [10–13]. Some of these methods have been considered in the present analysis, using different criteria to define the actual capacity utilizing the relationship between the applied load and the corresponding pile head settlement.

This paper reviews an extensive database of 135 load tests of driven and drilled piles in cohesionless soils. The pile load tests are used to evaluate the static analysis approach presented in the current Canadian Foundation Engineering Manual [14]. Furthermore, the ultimate pile capacities obtained using the CFEM method is compared with the results of other theoretical methods such as the standards of the American Association of State Highway and Transportation Officials [15], the Federal Highway Administration [16,17], the American Petroleum Institute [18,19], the Eurocode [20], and the Naval Facilities Engineering Command design method [21]. Besides, the paper considers three definitions of pile capacity evaluation from pile load tests to determine the actual ultimate pile load based on the load-displacement relationship obtained from each pile load test: namely, the Hansen 80% [22], Chin-Kondner [23,24], and the Decourt [25] methods.

Finally, an improved pile design procedure is proposed linking the pile design coefficients (β) and (N_t) to the friction angle of the soil, rather than employing the generalized soil type grouping scheme previously used in the CFEM. This improvement shall produce a more unified value of the pile capacity calculated by different designers, reducing the obtained design capacity discrepancies.

2. Pile Load Tests

When piles are used in critical projects, the design should be based not only on theoretical calculations but also on full-scale field tests of random piles to assure the expected working pile capacity. Pile load tests are the most accurate methods for determining the ultimate pile capacity. They are performed by applying a static axial load to the pile head and determine the corresponding response of the pile head. Such tests aim to ensure that the load capacity of the constructed pile is larger than the calculated capacity obtained in the design. This paper utilizes an extensive database of 135 load tests of driven and drilled (bored) piles in mostly cohesionless soils with a low percentage of silt [26,27].

During the installation of driven piles, the driving force displaces the soil while pushing the pile into the soil stratum, increasing the pile and the pile group capacities. In the case of drilled piles, boring of the soil reduces the lateral confinement around the pile, thus decreasing the capacity of the pile and the pile group. However, drilled piles are preferred in sites where pile driving is not permitted due to high vibration and noise levels. Pile load tests are usually represented by plotting the pile head settlement (displacement) on the y -axis against the applied load on the x -axis. In order to discuss and analyze the field results, three methods were used to find the ultimate load capacity of each pile. The methods used were the Hansen 80%, the Chin-Kondner, and the Decourt methods. Hansen [22] defined pile capacity as the load that results in pile head settlement four times greater than the settlement occurring at 80% of that load. This value can be determined by plotting the square root of the settlement divided by the corresponding load ($\sqrt{\delta/P}$) against that settlement value (δ). Chin [23,24] applied the work performed by Kondner [28] to piles. In the Chin method, the ratio between the settlement and the corresponding load (δ/P) is plotted against the settlement (δ). Then, the value of the ultimate capacity is given by the inverse of the slope of the resulting line. Finally, Decourt [25] defined a method similar to the methods of Hansen and Chin-Kondner to compute the actual pile capacity. In the Decourt method, the ratio between each load and the corresponding settlement (P/δ) is plotted against the load (P). The ultimate load is then identified by the intersection of the linear regression (using the last five points) of the curve with the x -axis (applied load).

3. Interpretation of the Friction Angle Used in the Design

As the scope of this paper is to evaluate the accuracy of the CFEM static design method currently utilized and compare it with other codes and field methods, the angle of internal friction which is used in most of these methods should be accordingly obtained utilizing the available field results. The friction angles of cohesionless soils can be estimated by using CPT results around the pile shaft and tip to calculate theoretical values for the side friction and tip bearing resistance. The following equation, presented by Kulhawy and Mayne [29], is commonly used to estimate the effective friction angle of cohesionless soils (φ') by using the CPT results (q_c) and the effective overburden stress (σ'_o):

$$\varphi' = \tan^{-1} \left[0.1 + 0.38 \log \left(\frac{q_c}{\sigma'_o} \right) \right] \quad (1)$$

The friction angles of cohesionless soils can also be estimated by using the SPT field results using the following equation by Schmertmann [30].

$$\varphi' = \tan^{-1} \left[\frac{N_{60}}{12.2 + 20.3 \left(\frac{\sigma'_o}{p_a} \right)} \right]^{0.34} \quad (2)$$

where N_{60} is the modified SPT number, σ'_o the effective overburden stress, and p_a is the atmospheric pressure.

4. The Theoretical Static Pile Design Method for Cohesionless Soils According to the CFEM

The total ultimate capacity for driven and drilled piles can be computed via the summation of the side shaft friction (Q_s) and the end bearing resistance (Q_t). The following equations present the overall criterion used to calculate the pile design value:

$$Q_{ult} = Q_s + Q_t \quad (3)$$

$$Q_s = q_s A_s \quad (4)$$

$$Q_t = q_t A_t \quad (5)$$

$$q_s = K_s \sigma'_o \tan \delta = \beta \sigma'_o \quad (6)$$

$$q_t = \sigma'_t N_t \quad (7)$$

where:

Q_{ult} = the theoretical ultimate pile capacity force

Q_s = the pile shaft resistance force

Q_t = the end bearing resistance force

q_s = the average unit shaft friction along the pile length, limiting values of q_s of about 100 kPa are recommended for displacement piles and 50 kPa for small displacement piles [31].

q_t = the bearing capacity at the pile toe, typical limiting values q_t range from 3–5 MN/m² for calcareous sand [2,32]

β = The combined shaft resistance coefficient

K_o = the coefficient of lateral earth pressure at rest

K_s = the coefficient of lateral earth pressure, $K_s \cong K_o$ for drilled piles, 1.4 K_o for low-displacement piles, and 2 K_o for high-displacement piles

σ'_o = the average effective overburden pressure along the pile shaft

σ'_t = the effective overburden pressure at the pile toe

δ = the friction angle between the pile and the surrounding soil

A_s = pile side surface area

A_t = pile tip cross-section area

The values of β and N_t depend on the friction angle of the cohesionless soil along the pile and at the pile tip, respectively. As shown in Table 1, the CFEM [14] presents ranges of β and N_t values according only to the general soil type classification. However, choosing an appropriate value from this table can be difficult if the soil classification alone is the only considered parameter. Besides, the experience of the designer in choosing appropriate values for β and N_t may result in calculated capacities that may vary widely between different designers resulting in large discrepancies in the calculated design capacity. As shown in Table 2, according to Meyerhof [33], cohesionless soils can be classified by using different ranges of the friction angle. The analyses in this paper, therefore, suggests combining the Meyerhof [33] soil classification criterion for cohesionless soils with the CFEM ranges of N_t values. Table 3 presents the suggested β and N_t values for ranges of relative densities and friction angles. A simple modification was introduced to the classification criterion presented in Table 2 to match those exhibited in the CFEM table (i.e., Table 1 in this paper) as presented in Table 3.

Table 1. β and N_t values, according to CFEM, for driven and drilled (bored) piles [14].

Soil Type	β		N_t	
	Drilled Piles	Driven Piles	Drilled Piles	Driven Piles
Silt	0.2–0.3	0.3–0.5	10–30	20–40
Loose sand	0.2–0.4	0.3–0.8	20–30	30–80
Medium sand	0.3–0.5	0.6–1.0	30–60	50–120
Dense sand	0.4–0.6	0.8–1.2	50–100	100–120
Gravel	0.4–0.7	0.8–1.5	80–150	150–300

Table 2. Correlation between relative density, SPT N value, and the internal friction angle for different cohesionless soils [15–17,33].

Soil Type	Friction Angle (ϕ')	Relative Density (D_r %)	SPT (N)
Very loose	<30	<20	<4
Loose	30–35	20–40	4–10
Compact (Medium)	35–40	40–60	10–30
Dense	40–45	60–80	30–50
Very dense	>45	>80	>50

Table 3. Suggested β and N_t values based on the soil classification and the CFEM ranges for driven and drilled (bored) piles.

Soil Type	Relative Density (%)	Friction Angle (ϕ')	β		N_t	
			Drilled (Bored) Piles	Driven Piles	Drilled (Bored) Piles	Driven Piles
Silt	–	<30	0.2–0.3	0.3–0.5	10–30	20–40
Loose sand	20–40	30–35	0.2–0.4	0.3–0.8	20–30	30–80
Medium sand	40–60	35–38	0.3–0.5	0.6–1.0	30–60	50–100
Dense sand	60–80	38–40	0.4–0.5	0.7–1.1	40–80	70–120
Very dense sand	>80	40–45	0.5–0.6	0.8–1.2	50–100	100–120
Gravel	–	>45	0.5–0.7	0.8–1.5	80–150	150–300

In the following analysis, the ultimate capacities of the 135 piles studied are calculated by using the β and N_t values based on the suggested classification in Table 3. These capacities are then compared with values estimated by using the other theoretical and field methods considered in this paper to evaluate the suitability of the suggested improvement.

5. Assessment of the CFEM Method for Estimating the Ultimate Pile Capacity in Cohesionless Soils

In accordance with the full-scale pile load tests described in Appendix A, the axial capacity for piles driven or drilled in cohesionless soil is calculated by using the CFEM static pile design method on the basis of the values suggested in Table 3. The results are then compared with results calculated from other codes and standards to assess the theoretical approach followed by the CFEM. In addition, the Hansen 80%, Chin-Kondner, and Decourt field methods are used to obtain the maximum actual capacity from the pile load-movement curves, and the values are also compared with those calculated by using the CFEM.

In the case of driven piles, it can be seen from Figure 1 that the majority of the axial capacities calculated by the CFEM method are lower when compared to the ASHTOO/FHWA, Eurocode, and the NAVFAC methods. However, the CFEM was found to produce a higher capacity when compared to the API design method, however, it is worth mentioning that the API was developed mainly for offshore piling. Figure 2a compares the pile capacities determined from the field results and the theoretical axial capacity calculated using the CFEM method. It can be noted from Figure 2a that most of the CFEM calculated pile capacities are comparable to the actual capacities obtained from the field methods with some variations. They are very close to capacities determined according to the Decourt [25] method. Likewise, it can be seen from Figure 2b that the average capacities for all field methods are close to the capacities calculated by the CFEM. Hence, it can be concluded that the axial load capacities for driven piles calculated using the CFEM method are within an acceptable range of the actual capacities.

Figure 1. Comparison between results of other design codes and the theoretical axial capacity in driven piles determined using the CFEM method.

Figure 2. Comparison between the theoretical axial capacity in driven piles determined using the CFEM method and (a) the field results, and (b) the average field results.

In the case of drilled (bored) piles, Figure 3 shows that most axial capacities calculated by the CFEM method are lower when compared to the Eurocode, the API, and the NAVFAC methods. However, the CFEM was found to produce a slightly higher capacity than the ASHTOO/FHWA design method. Figure 4a presents a comparison between the pile capacities determined from the field results and the theoretical axial capacity calculated using the CFEM method. It can be noted from Figure 4a that most of the CFEM calculated pile capacities are lower than the actual capacities obtained from the field methods and are very close to capacities determined according to the Decourt [25] method. Likewise, it can be seen from Figure 4b that the average capacities for all field methods are higher than the capacities calculated by the CFEM. Hence, it can be concluded that the axial load capacities for drilled piles calculated using the CFEM method are within a conservative range of the actual capacities.

Figure 3. Comparison between results of other design codes and the theoretical axial capacity in drilled (bored) piles determined using the CFEM.

Figure 4. Comparison between the theoretical axial capacity in drilled (bored) piles determined using the CFEM method and (a) the field results, and (b) the average field results.

6. Summary and Conclusions

Several pile design methods are used to estimate the expected pile load capacity. This paper evaluates the approach used in the CFEM for driven and drilled piles in cohesionless soils using a large database of pile load tests. The CFEM design method was also compared to the design methods from other codes and standards such as the American Association of State Highway and Transportation Officials, Federal Highway Administration, American Petroleum Institute, Eurocode, and the Naval Facilities Engineering Command. Moreover, an improved pile design procedure is proposed linking the pile design coefficients (β) and (N_f) to the friction angle of the soil, rather than employing the generalized soil type grouping scheme previously used in the current CFEM method. This improvement included in the new version of the CFEM 2021 shall produce a more unified value of the pile capacity calculated by different designers, reducing the obtained design capacity discrepancies. The results show that the CFEM static design method for driven piles gives a pile capacity that is within an acceptable range of the actual capacities. In the case of drilled (bored) piles, the CFEM values are a little bit conservative compared to the actual capacities.

Author Contributions: Conceptualization, H.E.N.; Data curation, I.E.; Investigation, H.E.N. and I.E.; Supervision, H.E.N.; Writing—original draft, H.E.N. and I.E.; Writing—review & editing, I.E. and H.E.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Natural Sciences and Engineering Research Council of Canada (NSERC) and Divert NS grant to the first author.

Data Availability Statement: All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Table A1. Load test locations and pile properties of driven piles.

Pile Test No.	Pile Location	Loading Type	Pile Material	Pile Shape	Length (m)	Width/Diameter (m)	Thickness (m)	Reference
1	Wuhu, China	compression	concrete	open circular	33	0.6	0.13	Yang et al., 2015a
2	Wuhu, China	compression	concrete	open circular	39.8	0.6	0.13	Yang et al., 2015a
3	Wuhu, China	compression	concrete	open square	39.8	0.5	0.095	Yang et al., 2015a
4	Wuhu, China	compression	concrete	open circular	29.3	0.6	0.13	Yang et al., 2015a
5	Wuhu, China	compression	concrete	open circular	29.2	0.8	0.13	Yang et al., 2015a
6	Rio de Janeiro Brazil	compression	concrete	square	37.2	0.5	0	Tsuha et al., 2012
7	Rio de Janeiro Brazil	compression	concrete	square	21.4	0.5	0	Tsuha et al., 2012
8	Rio de Janeiro Brazil	compression	concrete	square	35.6	0.7	0	Tsuha et al., 2012
9	Rio de Janeiro Brazil	compression	concrete	square	26.5	0.5	0	Tsuha et al., 2012
10	Blessington Dublin, Ireland	tension	steel	open circular	7	0.34	0.014	Gavin et al., 2013
11	Blessington Dublin, Ireland	tension	steel	open circular	7	0.34	0.014	Gavin et al., 2013
12	Horstwalde, Germany	tension	steel	open circular	17.61	0.711	0.0125	Rucker et al., 2013
13	Horstwalde, Germany	tension	steel	open circular	17.69	0.711	0.025	Rucker et al., 2013
14	Horstwalde, Germany	tension	steel	open circular	17.71	0.711	0.0125	Rucker et al., 2013
15	Horstwalde, Germany	tension	steel	open circular	17.76	0.711	0.0125	Rucker et al., 2013
16	Horstwalde, Germany	tension	steel	open circular	17.67	0.711	0.0125	Rucker et al., 2013
17	Horstwalde, Germany	tension	steel	open circular	17.66	0.711	0.0125	Rucker et al., 2013
18	Horstwalde, Germany	tension	steel	open circular	17.63	0.711	0.0125	Rucker et al., 2013
19	Horstwalde, Germany	tension	steel	open circular	17.74	0.711	0.0125	Rucker et al., 2013
20	British Columbia, Canada	compression	steel	circular	45	0.61	0	Naesgaard et al., 2012
21	Hampton, Virginia, USA	compression	concrete	square	16.8	0.61	0	Pando et al., 2003
22	Rotterdam Harbor, The Netherlands	compression	concrete	square	30.6	0.38	0	Gijt et al., 1995
23	Rotterdam Harbor, The Netherlands	compression	concrete	square	30.3	0.38	0	Gijt et al., 1995
24	Rotterdam Harbor, The Netherlands	compression	concrete	square	30.7	0.38	0	Gijt et al., 1995
25	Waddinxveen Site, The Netherlands	compression	concrete	square	10	0.35	0	Holscher et al., 2008
26	Mobile Bay, AL, USA	compression	steel	open circular	15.2	0.324	0.0254	Mayne & Niazi, 2013
27	ABEF Foundation, Brazil	compression	concrete	open circular	9	0.5	0.09	Mayne & Niazi, 2013
28	ABEF Foundation, Brazil	compression	concrete	open circular	7.5	0.5	0.09	Mayne & Niazi 2013
29	Apalachicola River, USA	compression	concrete	square	29.9	0.61	0	Mayne & Niazi 2013
30	Los Angeles, CA Site, USA	compression	concrete	square	29	0.61	0	Mayne & Niazi 2013
31	MS Smith, USA	compression	concrete	square	10.2	0.41	0	Mayne & Niazi 2013

Table A1. Cont.

Pile Test No.	Pile Location	Loading Type	Pile Material	Pile Shape	Length (m)	Width/Diameter (m)	Thickness (m)	Reference
32	MS Desota, USA	compression	concrete	square	7.6	0.46	0	Mayne & Niazi 2013
33	MS Harrison, USA	compression	concrete	square	7.6	0.46	0	Mayne & Niazi 2013
34	Washington MS, USA	compression	concrete	square	7.6	0.41	0	Mayne & Niazi 2013
35	Washington MS, USA	compression	concrete	square	16.6	0.36	0	Mayne & Niazi 2013
36	Washington MS, USA	compression	concrete	square	6.18	0.36	0	Mayne & Niazi 2013
37	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
38	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
39	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
40	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
41	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
42	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
43	Larvik, Norway	tension	steel	open circular	21.5	0.508	0.0063	Karlsrud 2014
44	Jackson County, USA	compression	steel	circular	17.8	0.273	0	Mayne & Elhakeim 2002
45	Lafayette Bridge, USA	compression	steel	circular	20.29	0.356	0	Komurka et al., 2010
46	Ogechee River, USA	compression	concrete	square	15.2	0.406	0	Vesic 1970
47	Ogechee River, USA	compression	steel	circular	6.1	0.457	0	Vesic 1970
48	Ogechee River, USA	compression	steel	circular	8.9	0.457	0	Vesic 1970
49	Ogechee River, USA	compression	steel	circular	12	0.457	0	Vesic 1970
50	Ogechee River, USA	compression	steel	circular	15	0.457	0	Vesic 1970
51	Drammen, Norway	compression	concrete	circular	8	0.28	0	Gregersen et al., 1973
52	Drammen, Norway	compression	concrete	circular	16	0.28	0	Gregersen et al., 1973
53	Drammen, Norway	compression	concrete	circular	7.5	0.28	0	Gregersen et al., 1973
54	Drammen, Norway	compression	concrete	circular	11.5	0.28	0	Gregersen et al., 1973
55	Drammen, Norway	compression	concrete	circular	15.5	0.28	0	Gregersen et al., 1973
56	Drammen, Norway	compression	concrete	circular	19.5	0.28	0	Gregersen et al., 1973
57	Drammen, Norway	compression	concrete	circular	23.5	0.28	0	Gregersen et al., 1973
58	Drammen, Norway	tension	concrete	circular	8	0.28	0	Gregersen et al., 1973
59	Drammen, Norway	tension	concrete	circular	16	0.28	0	Gregersen et al., 1973
60	Drammen, Norway	tension	concrete	circular	23.5	0.28	0	Gregersen et al., 1973
61	Hoogzand, The Netherlands	compression	steel	open circular	5.3	0.356	0.02	Beringen et al., 1979
62	Hoogzand, The Netherlands	compression	steel	circular	6.8	0.356	0	Beringen et al., 1979
63	Hunter's Point, USA	compression	steel	circular	7.8	0.273	0	Briaud et al., 1989a
64	Leman BD, North Sea	tension	steel	open circular	38.1	0.66	0.019	Chow et al., 1998
65	Baghdad University, Iraq	compression	concrete	square	11	0.253	0	Altaee et al., 1992
66	Baghdad University, Iraq	tension	concrete	square	11	0.253	0	Altaee et al., 1992
67	Baghdad University, Iraq	compression	concrete	square	15	0.253	0	Altaee et al., 1992
68	Dunkirk CLAROM, France	tension	steel	open circular	11.3	0.324	0.0127	Chow 1997

Table A1. Cont.

Pile Test No.	Pile Location	Loading Type	Pile Material	Pile Shape	Length (m)	Width/Diameter (m)	Thickness (m)	Reference
69	Dunkirk CLAROM, France	compression	steel	open circular	11.3	0.324	0.0127	Chow 1997
70	Dunkirk GOPAL, France	tension	steel	open circular	19.3	0.457	0.0135	Jardine et al., 2006
71	Dunkirk GOPAL, France	compression	steel	open circular	10	0.457	0.0135	Jardine et al., 2006
72	Dunkirk GOPAL, France	tension	steel	open circular	10	0.457	0.0135	Jardine et al., 2006
73	Locks and Dam, USA	compression	steel	circular	14.2	0.305	0	Briaud et al., 1989b
74	Locks and Dam, USA	compression	steel	circular	14.4	0.356	0	Briaud et al., 1989b
75	Locks and Dam, USA	compression	steel	circular	14.6	0.406	0	Briaud et al., 1989b
76	Locks and Dam, USA	tension	steel	circular	11	0.305	0	Briaud et al., 1989b
77	Locks and Dam, USA	tension	steel	circular	11.1	0.305	0	Briaud et al., 1989b
78	Locks and Dam, USA	tension	steel	circular	11	0.406	0	Briaud et al., 1989b
79	Hsin-Ta, Taiwan	compression	steel	circular	34.3	0.609	0	Yen et al., 1989
80	Hsin-Ta, Taiwan	tension	steel	circular	34.3	0.609	0	Yen et al., 1989
81	Hsin-Ta, Taiwan	compression	steel	circular	34.3	0.609	0	Yen et al., 1989
82	Drammen, Norway	compression	steel	open circular	11	0.813	0.0125	Tveldt & Fredriksen 2003
83	Cimarron River, USA	compression	steel	circular	19	0.66	0	Nevels & Snethen 1994
84	Jonkoping, Sweden	compression	concrete	square	16.8	0.235	0	Jendeby et al., 1994
85	Jonkoping, Sweden	compression	concrete	square	17.8	0.235	0	Jendeby et al., 1994
86	Jonkoping, Sweden	compression	concrete	square	16.2	0.275	0	Jendeby et al., 1994
87	Fittja Straits, Sweden	compression	concrete	square	12.8	0.235	0	Axelsson 2000
88	Fittja Straits, Sweden	compression	concrete	square	13	0.235	0	Axelsson 2000
89	Sermide, Italy	compression	steel	circular	35.9	0.508	0	Appendino 1981
90	Pigeon River, USA	compression	steel	circular	6.9	0.356	0	Paik et al., 2003
91	Pigeon River, USA	compression	steel	open circular	7	0.356	0.032	Paik et al., 2003

Table A2. Load test locations and pile properties of drilled (bored) piles.

Pile Test No.	Pile Location	Loading Type	Pile Material	Pile Shape	Length (m)	Width/Diameter (m)	Thickness (m)	Reference
1	Not available	compression	concrete	circular	13	1.1	0	Alsamman 1995
2	Berlin, Germany	compression	concrete	circular	5.8	0.421	0	Alsamman 1995
3	Hamburg, Germany	compression	concrete	circular	10.2	0.32	0	Alsamman 1995
4	Evanston, USA	compression	concrete	circular	15.2	0.457	0	Alsamman 1995
5	California, USA	compression	concrete	circular	6.5	0.393	0	Alsamman 1995
6	California, USA	compression	concrete	circular	5.6	0.41	0	Alsamman 1995
7	Hamburg, Germany	compression	concrete	circular	10.2	0.32	0	Alsamman 1995
8	Hamburg, Germany	compression	concrete	circular	7.7	0.32	0	Alsamman 1995
9	California, USA	compression	concrete	circular	9.2	0.403	0	Alsamman 1995
10	Houston, USA	compression	concrete	circular	24.2	0.814	0	Alsamman 1995
11	Hamburg, Germany	compression	concrete	circular	10.2	0.32	0	Alsamman 1995
12	Dusseldorf, Germany	compression	concrete	circular	13	0.671	0	Alsamman 1995

Table A2. Cont.

Pile Test No.	Pile Location	Loading Type	Pile Material	Pile Shape	Length (m)	Width/Diameter (m)	Thickness (m)	Reference
13	Not available	compression	concrete	circular	9.5	1	0	Alsamman 1995
14	Not available	compression	concrete	circular	9	1	0	Alsamman 1995
15	Guimaraes, Portugal	compression	concrete	circular	7.2	0.6	0	Alsamman 1995
16	Not available	compression	concrete	circular	9	1.1	0	Alsamman 1995
17	Berlin, Germany	compression	concrete	circular	10.2	0.5	0	Alsamman 1995
18	Berlin, Germany	compression	concrete	circular	6.2	0.329	0	Alsamman 1995
19	Berlin, Germany	compression	concrete	circular	5.8	0.408	0	Alsamman 1995
20	Berlin, Germany	compression	concrete	circular	8.2	0.521	0	Alsamman 1995
21	California, USA	compression	concrete	circular	8.4	0.405	0	Alsamman 1995
22	California, USA	compression	concrete	circular	10.4	0.405	0	Alsamman 1995
23	Berlin, Germany	compression	concrete	circular	7.8	0.399	0	Alsamman 1995
24	Dusseldorf, Germany	compression	concrete	circular	10.2	0.671	0	Alsamman 1995
25	Berlin, Germany	compression	concrete	circular	8.7	0.43	0	Alsamman 1995
26	Hamburg, Germany	compression	concrete	circular	7.7	0.32	0	Alsamman 1995
27	Berlin, Germany	compression	concrete	circular	10	0.399	0	Alsamman 1995
28	Kallo, Belgium	compression	concrete	circular	12	0.6	0	Alsamman 1995
29	Kallo, Belgium	compression	concrete	circular	12	0.6	0	Alsamman 1995
30	Shandong, China	compression	concrete	circular	27	1.1	0	Alsamman 1995
31	Hamburg, Germany	compression	concrete	circular	7.7	0.32	0	Alsamman 1995
32	Sao Paulo, Brazil	compression	concrete	circular	9.4	0.4	0	Eslami 1996
33	Seattle, USA	compression	concrete	circular	15.8	0.35	0	Eslami 1996
34	Berlin, Germany	compression	concrete	circular	10.2	0.5	0	Alsamman 1995
35	California, USA	compression	concrete	circular	7.9	0.405	0	Alsamman 1995
36	Not available	compression	concrete	circular	6	1.1	0	Alsamman 1995
37	Netherlands	compression	concrete	circular	18.3	0.631	0	Alsamman 1995
38	Berlin, Germany	compression	concrete	circular	8.2	0.521	0	Alsamman 1995
39	California, USA	compression	concrete	circular	7	0.405	0	Alsamman 1995
40	Berlin, Germany	compression	concrete	circular	7.8	0.4	0	Alsamman 1995
41	Hamburg, Germany	compression	concrete	circular	7.7	0.32	0	Alsamman 1995
42	Atlanta, USA	compression	concrete	circular	16.8	0.762	0	Alsamman 1995
43	Berlin, Germany	compression	concrete	circular	8.7	0.43	0	Alsamman 1995
44	Berlin, Germany	compression	concrete	circular	6.3	0.329	0	Alsamman 1995

References

- Terzaghi, K.; Peck, R.B. *Soil Mechanics in Engineering Practice*, 2nd ed.; Wiley: New York, NY, USA, 1967.
- Poulos, H.G. Pile Behaviour—Theory and Application. *Geotechnique* **1989**, *39*, 365–415. [[CrossRef](#)]
- Wong, K.C.; Poulos, H.G.; Thorne, C.P. *Development of Expert Systems for Pile Foundation Design*; University of Sydney: Sydney, Australia, 1991; Volume CE33, No. 2, IE Aust.
- Hossain, M.Z.; Abedin, M.Z.; Rahman, M.R.; Haque, M.N.; Jadid, R. Effectiveness of sand compaction piles in improving loose cohesionless soil. *Transp. Geotech.* **2021**, *26*, 100451. [[CrossRef](#)]
- Alnuaim, A.M.; El Naggar, M.H.; El Naggar, H. Performance of micropiled rafts in clay: Numerical investigation. *Comput. Geotech.* **2018**, *99*, 42–54. [[CrossRef](#)]
- Alnuaim, A.M.; El Naggar, H.; El Naggar, M.H. Evaluation of Piled Raft Performance Using a Verified 3D Nonlinear Numerical Model. *Geotech. Geol. Eng.* **2017**, *35*, 1831–1845.
- Gaaver, K.E. Uplift capacity of single piles and pile groups embedded in cohesionless soil. *Alex. Eng. J.* **2013**, *52*, 365–372. [[CrossRef](#)]
- El Kamash, W.; El Naggar, H. Numerical Study on Buckling of End-Bearing Piles in Soft Soil Subjected to Axial Loads. *Geotech. Geol. Eng.* **2018**, *36*, 3183–3201. [[CrossRef](#)]
- Birid, K.C. Evaluation of Ultimate Pile Compression Capacity from Static Pile Load Test Results. In *Advances in Analysis and Design of Deep Foundations, Proceedings of the International Congress and Exhibition “Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology, Sharm El Sheikh, Egypt, 15–19 July 2017*; Springer: Cham, Switzerland, 2017.
- Fellenius, B.H. Test loading of piles. Methods, interpretation, and new proof testing procedure. *ASCE J. Geotech. Eng. Div.* **1975**, *101*, 855–869. [[CrossRef](#)]
- Fellenius, B.H. The analysis of results from routine pile loading tests. *Ground Eng.* **1980**, *13*, 19–31.
- Fellenius, B.H. *What Capacity Value to Choose from the Results a Static Loading Test*; Deep Foundation Institute, Fulcrum: Hawthorne, NJ, USA, 2001.

13. Almallah, A.; El Naggar, H.; Sadeghian, P. Axial Behaviour of Innovative Sand-Coated GFRP Piles in Cohesionless Soil. *Int. J. Geomech.* **2020**, *20*, 04020179. [[CrossRef](#)]
14. Canadian Geotechnical Society. *Canadian Foundation Engineering Manual*, 4th ed.; BiTech Publishing Ltd.: Richmond, BC, Canada, 2006.
15. American Association of State Highway and Transportation Officials (AASHTO). *Standard Specifications for Highway Bridges*; Transportation Officials: Washington, DC, USA, 2020.
16. FHWA Drilled Shafts Manual. *Construction Procedures and LRFD Design Methods Reference Manual*; FHWA-NHI-10-016; Federal Highway Administration Publication: Woodbury, MN, USA, 2010.
17. FHWA Driven Pile Manual. *Design and Construction of Driven Pile Foundations Reference Manual*; FHWA-NHI-16-009; Federal Highway Administration Publication: Woodbury, MN, USA, 2016; Volume 1.
18. American Petroleum Institute (API). *API Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design*; API: Washington, DC, USA, 2003.
19. American Petroleum Institute (API). *API Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design*; API: Washington, DC, USA, 2014.
20. EU. BS EN. 1997-2:2007. *Eurocode 7: Geotechnical Design—Part 1: General Rules. Part 2: Ground Investigation and Testing*; EU: Maastricht, The Netherlands, 2007.
21. NAVFAC DM 7.2. *Foundation and Earth Structures*; U.S. Department of the Navy: Washington, DC, USA, 1986.
22. Hansen, J.B. Discussion on hyperbolic stress-strain response. Cohesive soils. *J. Soil Mech. Found. Div. ASCE* **1963**, *89*, 241–242. [[CrossRef](#)]
23. Chin, F.K. Estimation of the Ultimate Load of Piles not Carried to Failure. In Proceedings of the 2nd Southeast Asian Conference on Soil Engineering, Singapore, 11–15 June 1970; pp. 81–90.
24. Chin, F.K. Discussion, Pile Tests-Arkansas River Project. *ASCE J. Soil Mech. Found. Eng.* **1971**, *97*, 930–932. [[CrossRef](#)]
25. Decourt, L. Behavior of foundations under working load conditions. In Proceedings of the 11th Pan-American Conference on Soil Mechanics and Geotechnical Engineering, Foz Do Iguaçu, Brazil, 8–12 August 1999; Volume 4, pp. 453–488.
26. Alkroosh, I.S.J. Modelling Pile Capacity and Load-Settlement Behaviour of Piles Embedded in Sand & Mixed Soils Using Artificial Intelligence. Ph.D. Dissertation, Department of Civil Engineering, Curtin University, Perth, Australia, 2011.
27. Yang, Z.; Guo, W.; Jardine, R.; Chow, F. *A Comprehensive Database of Tests on Axially Loaded Piles Driven in Sand*; Zhejiang University Press Co., Ltd.: Hangzhou, China; Elsevier: London, UK, 2016.
28. Kondner, R. Hyperbolic Stress-Strain Response of Cohesive Soils. *J. Soil Mech. Found. Div.* **1963**, *89*, 115–143. [[CrossRef](#)]
29. Kulhawy, F.H.; Mayne, P.W. *Manual on Estimating Soil Properties for Foundation Design*; Electric Power Research Institute: Palo Alto, CA, USA, 1990.
30. Schmertmann, J.H. Measurement of In-Situ Shear Strength. In Proceedings of the Geotechnical Specialty Conference on In Situ Measurement of Soil Properties, Raleigh, NC, USA, 1–4 June 1975; Volume 2, pp. 57–138.
31. Poulos, H.G.; Carter, J.P.; Small, J.C. Foundations and retaining structures—Research and Practice. In Proceedings of the 15th International Conference on Soil Mechanics and Geotechnical Engineering, Istanbul, Turkey, 27–31 August 2001; Volume 4, pp. 2527–2606.
32. Nauroy, J.-F.; Brucy, F.; Le Tirant, P.; Kervadec, J.-P. Design and installation of piles in calcaieous formations. In Proceedings of the 3rd International Conference on Numerical Methods in Offshore Piling, Nantes, France, 21–22 May 1986; p. 61480.
33. Meyerhof, G.G. Penetration Tests and Bearing Capacity of Cohesionless Soils. *J. Soil Mech. Found. Div.* **1956**, *82*, 1–19. [[CrossRef](#)]