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COMPARISON OF FIELD PILE LOAD TESTS WITH THE THEORETICAL STATIC EQUATIONS USING SOIL PARAMETERS

Samuel Akinlabi Ola, Bernard Chukwuemeka Finbarrs-Ezema*, Ige Ayodeji Oluwasegun

Afe Babalola University, Department of Civil Engineering, KM 8.5 Afe Babalola Way, Ado Ekiti, Ekiti, Nigeria
* corresponding author: `finbarrs-ezemabc@abuad.edu.ng`

Abstract. Pile bearing capacity is simply the maximum load that a pile can withstand before excessive settlement. Its estimation is usually complex due to various factors, such as installation techniques, construction methods, and ground conditions. Validating pile designs through testing is important in order to ensure reliability and address any uncertainties that may arise during the design and construction phases. This research paper presents a comprehensive comparison of field pile load tests with theoretical static equations for determining the bearing capacity of pile foundations. The study focuses on the accuracy of static equations in estimating the bearing capacity of piles in cohesive soils. The research analysed twenty different cases involving bored piles in cohesive soils and compared the results with actual field pile load tests. The findings of the study indicate that this research is able to predict the bearing capacity of a cohesive soil that will be in close agreement with the results of field pile load test results for cohesive soils. Static equations are generally accurate in estimating the ultimate bearing capacity of piles but can be improved by conducting thorough soil investigations and lab testing for a more accurate representation of the soil parameters. The study recommends the use of static equations as an initial assessment tool, but also emphasises the importance of conducting field load tests to confirm their accuracy. The Tangent method is also recommended for adoption as a standard practice in pile design alongside the static equations, as both had correlation coefficients of 0.95 with the pile loading tests. The results of this study provide valuable insights for engineers and researchers involved in the design and construction of deep foundations, highlighting the accuracy and usefulness of static equations.

Keywords: Pile load test, pile static equations, pile bearing capacity, cohesive soils, bored piles, tangent method.

1. Introduction

A pile is a relatively small-diameter shaft-driven or installed into the ground using various methods. Piles can withstand vertical loads, horizontal loads, or a combination of both. They are often installed in groups to serve as foundations for structures [1]. The foundation, which is a component of any building structure, transmits superimposed loads from the structure to the soil. It is a group of structural elements designed to distribute the weight of the building and its contents to the ground without exceeding the maximum stress or failing [2]. A pile is a type of deep foundation. The primary function of a foundation is to provide stability to the structure by transmitting loads and resisting soil settlements, ensuring the structure remains secure and safe for its occupants.

Foundation design relies on four main sources for bearing capacity information: building codes and experience-based tables in design books and official guides, on-site soil loading tests, model laboratory tests with soil samples from the site, and theoretical static equations [1]. In order to accurately determine the bearing capacity of piles, theories and equations have been developed. Pile load tests and the use of static equations are both key aspects of pile design, both are commonly used to determine the bearing capacity of piles. In this project, the bearing capacity results of field load tests will be compared with those of static equations. The comparison of field pile load tests with static equations is important to determine the accuracy of the static equations in estimating pile bearing capacity. This project uses field pile load tests conducted on drilled or bored piles. The internet and other means were used to search for works involving field pile loads and soil parameters in order to calculate the bearing capacity static equations for comparison.

The objective of this paper is not to formulate new procedures for Static Load Tests. These have been done through different building codes, such as ASTM – 1143; BS 8004 and Eurocode 7; IS 2911. The objective is to develop a new method of pile capacity calculations that are in close agreement with field pile loading test results using soil parameters. To develop this new method, reference is made to the works of Tomlinson [3], Teng [4], Terzaghi and Peck [5], and Ola [1] which state that pile driving in soft clays tends to disturb the clay around the pile. The disturbed clay begins to consolidate and gain strength rapidly and immediately after the driving. Pile driving in stiff clays not only disturbs the surrounding soil, but it may also create a small open space between the pile and the clay. Consequently, the adhesion is always smaller than the cohesive or shear strength of the soil. Unless proven by pile load test, the values in Table 1 are recommended. This paper has used Table 1 and used the relationship $c_a = kC_u$. Several values were assumed for k to obtain c_a for the analysis.

Table 1 presents information on the adhesion of driven piles to concrete, timber, and steel. However, only the adhesion to concrete was used, as all of the piles were made of concrete. Also, the driven piles give the worst-case situation with respect to adhesion. With time, there is an increase in strength. For a drilled pile, the reduction in strength of the surrounding soil is less than that of a driven pile.

The study involves the collection of data on the required pile load test results, estimating the bearing capacity of the piles using the static equations, comparing the results, and analysing the results. The outcomes of this study will help to determine the reliability and accuracy of the static equations, improving pile design and structural safety.

1.1. Problem statement

Static equations are commonly used to estimate the bearing capacity of pile foundations. However, the accuracy of these equations is often questioned because soil parameters vary and the load transfer mechanisms are complex. Pile load tests are conducted to validate the static equations and to provide a more accurate estimate of the bearing capacity of pile foundations. Determining the accuracy of the static equations and identifying the factors that affect the accuracy is challenging, and if not properly understood, it can result in pile foundations being either over- or under-designed, leading to safety risks.

1.2. Aim and objectives

The aim of this study is to compare the results of field pile load tests with those of the static equations. The objectives are:

(1.) To evaluate the accuracy of static equations in estimating the bearing capacity of pile foundations.

(2.) To identify the factors that affect the accuracy of the equations such as the soil parameters.

(3.) To develop a new method of pile capacity calculations that are in close agreement with field pile loading test results using soil parameters.

(4.) To provide recommendations based on the findings of the project. The research will correlate the various methods to present a bearing capacity, which can be relied upon even without the use of pile tests.

Material of pile	**Cohesion $c = \frac{q_u}{2}$ [kN m^{-2}]**	**Adhesion c_a [kN m^{-2}]**
Concrete and timber	0	0
	36	33.5
	72	48
	144 or greater	62
Steel	0	0
	36	33.5
	72	48
	144 or greater	58

Table 1. Ultimate values of skin friction (adhesion) for piles embedded in cohesive soils [1].

1.3. Significance of study

Testing of the piles is a very important part of designing a pile foundation, as it helps to determine their bearing capacity and addresses any uncertainties that may arise during the design or construction. This research shows a comparison of bearing capacity from field pile load tests and static equations in order to help designers identify shortcomings in the equations and pile load tests. It also provides insight into whether the measured or estimated bearing capacity is better, thereby eliminating a lot of uncertainties.

The identified gap is that currently, until a pile loading test is done, the bearing capacity of a pile cannot be accurately determined. The research significance is that the findings of the study indicate that it is possible to predict the bearing capacity of a cohesive soil that will be in close agreement with the results of field pile loading test results for cohesive soils. The novelty of the work is that by using iteration and linear regression analyses, a complex problem has been brought to a satisfactory solution for cohesive soils.

1.4. Limitation of study

This study primarily focuses on drilled or bored piles, specifically those in cohesive soils. The work uses a limited database. The research analysed various cases involving bored piles in cohesive soils. As more data are available, the database will increase. Also, the work uses conventional methods and procedures to compute the bearing capacity of piles using iteration and linear regression analyses that most geotechnical engineers can follow. More refined methods of artificial intelligence may follow later. The current work is limited to cohesive soils only and is not applicable to other soils. Further research is required to extend it to all soils. Also, the current work depends on the quality of the field and laboratory work to determine the shear strength of the cohesive soil. Further research is required in the areas of thorough site-specific soil investigations and laboratory soil testing. It is strongly noted that in this study, static equations were only correlated with static load test results. Therefore, these findings should only be applied to the control and calibration of pile design methods as every site

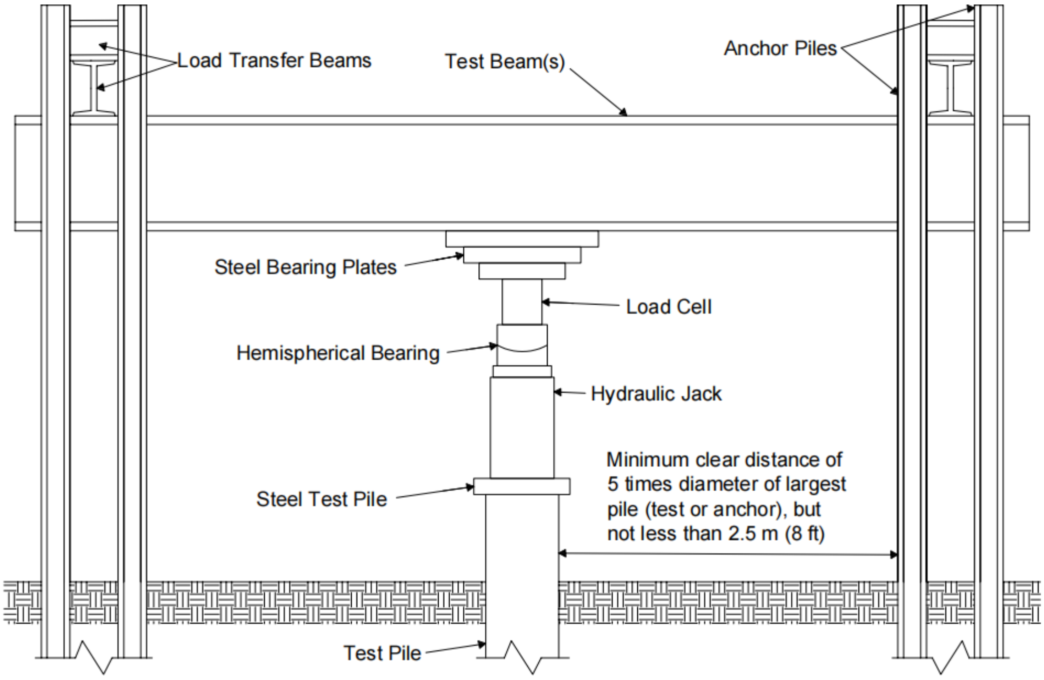

Figure 1. Static pile load test setup.

presents specific conditions that require the utmost caution and professional guidance.

1.5. Justification of study

Depending on the accuracy of the static equations, the additional cost of carrying out pile load tests can be reduced. Understanding the strengths and weaknesses of both the pile load tests and static equations will help engineers select the most appropriate approach for assessing the bearing capacity of piles in different project scenarios. Also, this research is able to predict the bearing capacity of a cohesive soil that will be in close agreement with the results of field pile loading test results for cohesive soils.

2. Literature review

The most direct and reliable approach to determine the pile bearing capacity is statically loading the pile up to its failure [6]. Static load tests can be classified based on their methodology as maintained load tests and the constant rate of penetration tests [7]. Figure 1 shows an experimental system for a static loading test, hydraulic presses are used to apply a vertical pressing force on the pile and measure the load applied [8]. In Krasiński and Wiszniewski's study [9], field data and numerical simulations of static load test on instrumented piles were compared. It was found that field data had lower friction values whereas numerical analysis predicted lower pile base resistance. Birid [10] compared and evaluated several approaches to determine the ultimate pile capacity by analysing load-settlement data from 23 static pile load tests conducted on driven piles and drilled shafts. Since every method estimated ultimate loads under various test loads differently, they were unable to suggest a single approach. Cherian [11] used a well instrumented bi-directional static load test to determine the pile-rock interactions, an increase in skin friction from the pile load test was observed when compared to initial design values obtained before the test. However, this increase was used to optimise the pile design. Currently, the standard practice of analysing static load test results is unsatisfactory [12], hence the need to revisit the use of traditional static equations. Multi-layered soil conditions can also make the interpretation of static pile load test results including bi-directional tests difficult [13].

Additionally, dynamic load testing is known for its speed, reliability, and cost-effectiveness in providing information about the performance of piles in various soil conditions and construction scenarios [14]. In Noor et al.'s work [15], seven dynamic load tests on six large-diameter piles were performed and the distribution of pile bearing resistance under static load was evaluated using the program DLTWAVE. They concluded that for very stiff to hard clay, the shaft resistance predicted with DLTWAVE was lower than that obtained from static formula. Souza et al. [16] contrasted the ultimate pile load determined by interpreting dynamic load tests with the expected geotechnical load capacity as determined by empirical and semi-empirical Brazilian methods. An excellent correlation between their findings and static load tests was observed.

According to Raison [17], the Berezantzev technique frequently yields more conservative values for N_q and N_γ, lower than those provided by many other theories. Several international design standards support the classical Meyerhof's static equation for determining the ultimate pile capacity [18]. The Meyerhof

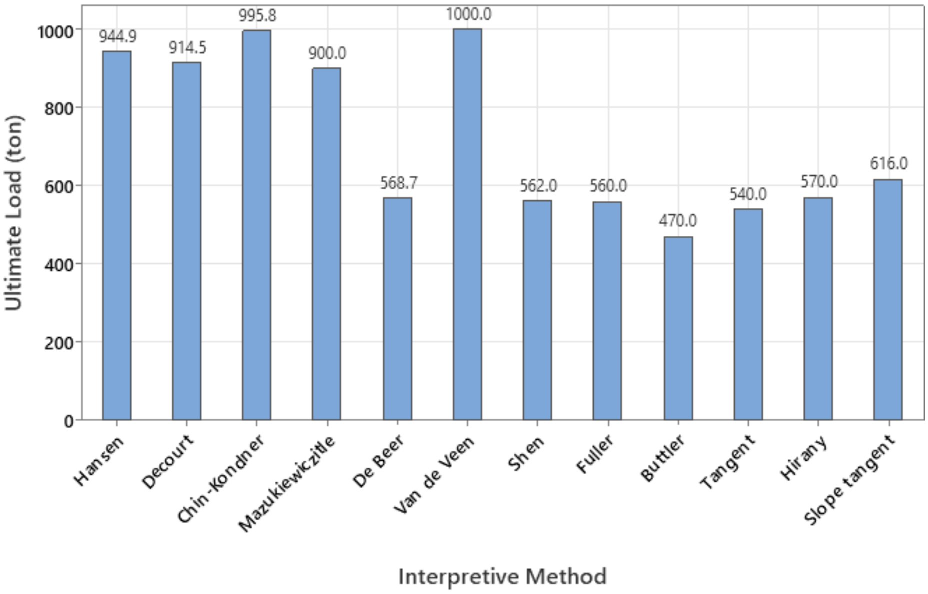

Figure 2. Bearing capacity interpretations from load tests [8].

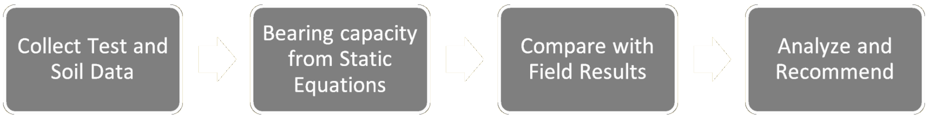

Figure 3. Research flow chart.

method was found to be too conservative after an estimation involving 113 pile load tests results [19]. In Oteuil et al.'s study [20], it was pointed out that Coyle and Castello's method, like other conventional methods, produces more conservative results for toe resistance. Also, in Rivera and Estores's research [21], Coyle and Castello method yielded a correlation coefficients of 0.62, 0.58, and 0.47 for ultimate capacity, shaft resistance and point bearing, respectively, when compared to pile dynamic test results. Vesic method and Indian standards were compared by analysing the lateral load capacity of piles based on six different borehole log details. Their results showed that the Indian standards are uneconomical and conservative [22].

Since a pile loaded to failure is a waste, pile bearing capacities are generally graphically interpreted from load test results (load settlement curves) before failure. Mahmood et al. [23] used 45 pile load tests conducted on the cast-in-situ (bored) piles to compare various pile capacity interpretation methods. They found that De Beer intersection load and Mazurkiewicz methods were the most reliable for bored piles. Adel and Shakir [8] compared 15 different interpretative methods. Chin-Kondner and Brinch Hansen method was found to estimate the highest ultimate load. Figure 2 shows only 12 of the 15 interpretive methods used. They concluded that the Van der Veen method results were not acceptable because it estimated the highest ultimate loads amongst all the methods. The average of the following seven methods, De Beer, Shen, Fuller, Buttler, Tangent, Hirany, and Slope tangent, is 555 tonnes. The Tangent method is 540 tonnes, which is less than 3 % from the average. This is one of the reasons for the choice of the Tangent method for this research.

3. Methodology

This section gives, in detail, the static equation used for the determination of ultimate pile bearing resistance, skin resistance, and point/base resistance for the purpose of this research. As simplified in Figure 3, the research flow chart shows that this study will determine the bearing capacity of soils based on soil parameters and static equations. Thereafter, comparisons and analysis will be done with field load test results. The research data were sourced from Reese and O'Neil [24]. Key information was extracted and highlighted in Table 2. Several advanced theories for the calculation of bearing capacities were reviewed and based on the review, Berezantsev, Meyerhof, Coyle and Castello, and Vesic methods were used in the calculation of the ultimate bearing capacity from the soil properties. Table 1 was utilised based on the works of Tomlinson [3], Teng [4], Terzaghi and Peck [5], and Ola [1]. The relationship $c_a = kC_u$ was also used. Several values of k were assumed to obtain c_a for the analysis. The values of ultimate bearing capacity obtained from this analysis was plotted against the ultimate bearing capacity obtained from the pile load test, and the linear correlation coefficient was determined. A sensitivity analysis was then carried out.

S/N	Case Nos.[a]	Diameter [m]	Length [m]	Soil profile	Construction procedure	Location	Ultimate load [kN]
1	Case 10	0.52	23.99	Clay[c]	Casing	Bangkok	2 038.10
2	Case 11	0.76	12.81	Clay	Dry/Casing	Bryan, Texas	3 782.50
3	Case 15	0.76	7.05	Clay	Dry	Houston, Texas	1 246.00
4	Case 16[b]	0.76	7.02	Clay	Dry	Houston, Texas	4 761.50
5	Case 17	0.76	13.73	Clay	Casing & Slurry, Dry	Houston, Texas	2 848.00
6	Case 21	1.20	25.01	Silty clay[c]	Dry/Casing	Bangkok	6 354.60
7	Case 22	1.00	25.28	Silty clay[c]	Dry/Casing	Bangkok	4 788.20
8	Case 23	1.00	26.02	Silty clay[c]	Dry/Casing	Bangkok	5 375.60
9	Case 30[b]	0.79	12.20	Clay	Dry	London	4 120.70
10	Case 31	0.63	9.30	Clay	Dry	London	756.50
11	Case 32[b]	0.63	9.24	Clay	Dry	London	2 118.20
12	Case 33[b]	0.62	12.17	Clay	Dry	London	2 589.90
13	Case 34	0.77	9.40	Clay	Dry	London	1 539.70
14	Case 35	0.77	12.23	Clay	Dry	London	2 429.70
15	Case 36	0.80	15.22	Clay	Dry	London	2 314.00
16	Case 37[b]	0.77	9.55	Clay	Dry	London	2 750.10
17	Case 38[b]	0.77	16.01	Clay	Dry	London	4 806.00
18	Case 39	0.94	15.25	Clay	Dry	London	3 506.60
19	Case 40[b]	0.94	12.72	Clay	Dry	London	5 963.00
20	Case 41[b]	0.94	16.26	Clay	Dry	London	5 874.00

[a] Case numbers as indexed in the source.

[b] Belled pile: diameter that constituted most of the pile length and the total length are presented.

[c] Mixed soil profile with silty clay and sandy clay: soil class that constituted most of the pile length is presented.

Table 2. Field data and pile load test results [24].

3.1. Research data

The pile load test data used in this study were sourced from the work of L. C. Reese and M. W. O'Neill, titled "Field Load Tests of Drilled Shafts", published in the compilation "Deep Foundations on Bored and Auger Piles," edited by Van Impe and published by Balkema in 1988 [24]. Only the data on boreholes drilled in cohesive soils were used in the current analysis. The analysis of this dataset is relevant because of the various locations explored and the adequate investigative details presented, which include borehole logs, shaft dimensions, detailed soil profiles, shear strength at various layers, load-settlement curves, professional comments, and construction procedures. Information on the kind of loading (short-term or sustained) was also provided. All the cases had quick loading except case 10 and case 22, where the loading was slow and sustained, respectively. Specific details including; methods of applying compressive loads, reaction shafts, load platforms, method of performing a pull-out test, instrumentation, design and construction of test shaft, testing procedures, and interpretation of failure, data and load/settlement analyses are well documented in Reese and O'Neill's work [24]. However, key information was extracted and highlighted in Table 2.

3.2. Theoretical static equations

Theoretical static equations, also called "Static bearing capacity equations", are used to estimate the load-carrying capacity of a pile. These equations are important in determining the ability of a pile to support loads (vertical, lateral) without experiencing failure. Essentially, these equations combine factors, such as the pile base/point resistance (Q_b), frictional resistance (Qs), bearing capacity factors (N_c, N_q, N_γ), unit weight of soil (γ), pile cross sectional area (A_p), and adhesion (c_a), to calculate the ultimate bearing capacity of a pile (Q_u). This section will look at the methods used in practice to calculate the ultimate loads of piles in cohesive soils. These methods in particular will be for piles subjected to axial compression.

In order to achieve the objectives, the first phase of the investigation focused on relatively large diameter piles. It also focused on bored (drilled) reinforced concrete piles to reduce the disturbances of the in-situ soils to a minimum. Pile tests that conform to the above were collected from different parts of the world. Twenty pile tests with adequate soil tests and soil parameters were selected for this analysis. The failure loads of piles were also determined from the pile load test using the Tangent method The Tangent method was selected because it gave the average of seven different methods, namely: De Beer, Shen, Fuller, Buttler, Tangent, Hirany, and Slope Tangent [8]. The method is also very easy to use. Soil investigation of the selected pile sites was studied to collect the soil parameters needed to calculate the ultimate bearing capacity of the soil using the soil mechanics formula.

There are several advanced theories for calculating the bearing capacity factors, including: Berezantsev, Meyerhof, Vesic, Jambu, Coyle and Castello, and

Layer	Thickness [m]	Soil profile	C_u [kN m^{-2}]
1_a*	0–7.05	Clay	$114.96^{(avg)}$
1_b	7.05–9.61	Clay	$109.20^{(avg)}$
1_c	9.61–12.21	Clay	$172.44^{(avg)}$
1_d	12.21–13.73	Clay	$214.02^{(avg)}$
1_{base}	13.73	Clay	214.60

* Water table is at 4.58 m below ground surface.

TABLE 3. Soil parameters for [24].

Meyerhof (Based on SPT). Tomlinson [25] recommends Berezantsev's method because in his opinion, the method conforms to the practical criteria of pile failure. Murthy [26] believes that Coyle and Castello's method is based on full scale field tests on a number of driven piles. His order of preference for the use of the various methods after a critical survey is as follows: Berezantsev, Meyerhof, Coyle and Castello, Meyerhof (SPT), Vesic, and Jambu. In view of this, the first three preferences and the Vesic method will be used in the calculations of the ultimate bearing capacity (Q_u) from the soil properties.

3.3. ESTIMATING PILE BEARING CAPACITY USING STATIC THEORETICAL SOIL MECHANICS FORMULA

The general soil mechanics formula for determining the ultimate bearing capacity Q_u of a pile is as follows [27]:

$$Q_u = Q_p + Q_s, \tag{1}$$

where:

Q_p is the point or base resistance:

$$Q_p = \pi r^2 (cN_c + q_b N_q), \tag{2}$$

Q_s is the skin, frictional, or shaft resistance for the pile:

$$Q_s = 2\pi r L f_s. \tag{3}$$

For round and cylindrical piles:

- For cohesive soils:

$$f_s = c_a. \tag{4}$$

- For cohesionless soils:

$$f_s = \frac{1}{2}(K_s \gamma' L \tan\delta) \tag{5}$$

$$\text{or } Q_s = 2\pi r L (q_o K_s \tan\delta), \tag{6}$$

where:

c the average cohesion of the soil around the pile tip,

N_c the bearing capacity factor showing the influence of cohesion and is equal to 9.0,

c_a the average adhesion of soil around the pile shaft,

r the pile radius,

L the pile length,

q_b the effective overburden pressure at the pile tip,

N_q the bearing capacity factor which shows the influence of surcharge,

K_s the average coefficient of earth pressure on the pile shaft,

q_o the average effective overburden pressure along the pile shaft,

$\tan\delta$ the angle of skin friction between the soil and the pile shaft,

f_s the unit skin friction or unit shaft resistance,

γ' the unit weight of soil, use buoyant weight for the portion below ground water.

In this paper, adhesion was estimated using $0.3C_u$, $0.4C_u$, and ultimate adhesion, which is shown in Table 1. These values are usually recommended in the literature [1].

		$0.3C_u$	**$0.4C_u$**	**Table 1**
1_a	c_a [kN m^{-2}]	34.49	45.98	56.35
	Q_s	580.81	774.30	948.93
1_b	c_a [kN m^{-2}]	32.76	43.68	55.23
	Q_s	200.49	267.32	338.01
1_c	c_a [kN m^{-2}]	51.73	68.98	62
	Q_s	321.24	428.37	385.02
1_d	c_a [kN m^{-2}]	64.21	85.61	62
	Q_s	233.08	310.76	225.06

TABLE 4. Skin Resistance Results for Layer 1_a, 1_b, 1_c, 1_d [24].

4. CASE STUDIES

Twenty cases were studied. A typical example of all the calculations involved in each case is presented in Section 4.1 (case 17). Table 3 shows the soil parameters and Table 4 shows the skin resistance results. Also, a summary of the bearing capacity values from the field data, static equation and the Tangent method is shown in Table 5.

	Pile load test [kN]	Static equation [kN]	Tangent method [kN]
Q_u	2 848	2 766.15	2 661.10
Q_s	1 568.18	1 897.02	
Q_b	1 253.12	869.13	

Table 5. Ultimate bearing capacity results [24].

4.1. Case 17: O'Neill & Reese 1970 Houston, Texas. Shaft S4 [24]

Pile dimensions:

- Diameter – 0.763 m,
- Length – 13.73 m.

Pile load test results:

- $Q_u = 2\,848\,\text{kN}$,
- $Q_s = 1\,568.18\,\text{kN}$,
- $Q_b = 1\,253.12\,\text{kN}$.

4.1.1. Base resistance

$$Q_b = N_c C_u A_b, \tag{7}$$

where:

- $N_c = 9$,
- $C_u = 214.60\,\text{kN}\,\text{m}^{-2}$,
- $A_b = \pi r^2 = \pi \times 0.38^2 = 0.45\,\text{m}^2$,

therefore:

$$Q_b = 9 \times 214.60 \times 0.45 = 869.13\,\text{kN}. \tag{8}$$

4.1.2. Skin resistance

Layer $1_\mathbf{a}$ Cohesive layer (Clay):

$$Q_s = 2\pi r L c_a, \tag{9}$$

where:

- $r = 0.38\,\text{m}$,
- $L = 7.05\,\text{m}$,
- $C_u = 114.96\,\text{kN}\,\text{m}^{-2}$,
- $Q_s = 2 \times 3.143 \times 0.38 \times 7.05 \times c_a = 16.84 c_a$,
- $C_u = \begin{cases} 0.3\times114.96 = 34.49\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.3, \\ 0.4\times114.96 = 45.98\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.4, \end{cases}$
- from Table 1: $c_a = 56.35\,\text{kN}\,\text{m}^{-2}$.

Layer $1_\mathbf{b}$ Cohesive layer (Clay):

$$Q_s = 2\pi r L c_a, \tag{10}$$

where:

- $r = 0.38\,\text{m}$,
- $L = 2.56\,\text{m}$,
- $C_u = 109.20\,\text{kN}\,\text{m}^{-2}$,
- $Q_s = 2 \times 3.143 \times 0.38 \times 2.56 \times c_a = 6.12 c_a$,
- $C_u = \begin{cases} 0.3\times109.20 = 32.76\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.3, \\ 0.4\times109.20 = 43.68\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.4, \end{cases}$
- from Table 1: $c_a = 55.23\,\text{kN}\,\text{m}^{-2}$.

Layer $1_\mathbf{c}$ Cohesive layer (Clay):

$$Q_s = 2\pi r L c_a, \tag{11}$$

where:

- $r = 0.38\,\text{m}$,
- $L = 2.60\,\text{m}$,
- $C_u = 172.44\,\text{kN}\,\text{m}^{-2}$,
- $Q_s = 2 \times 3.143 \times 0.38 \times 2.60 \times c_a = 6.21 c_a$,
- $C_u = \begin{cases} 0.3\times172.44 = 51.73\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.3, \\ 0.4\times172.44 = 68.98\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.4, \end{cases}$
- from Table 1: $c_a = 62\,\text{kN}\,\text{m}^{-2}$.

Layer $1_\mathbf{d}$ Cohesive layer (Clay):

$$Q_s = 2\pi r L c_a, \tag{12}$$

where:

- $r = 0.38\,\text{m}$,
- $L = 1.52\,\text{m}$,
- $C_u = 214.02\,\text{kN}\,\text{m}^{-2}$,
- $Q_s = 2 \times 3.143 \times 0.38 \times 1.52 \times c_a = 3.63 c_a$,
- $C_u = \begin{cases} 0.3\times214.02 = 64.21\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.3, \\ 0.4\times214.02 = 85.61\,\text{kN}\,\text{m}^{-2} & \text{when } c_a = 0.4, \end{cases}$
- from Table 1: $c_a = 62\,\text{kN}\,\text{m}^{-2}$.

4.1.3. Ultimate bearing capacity

$$Q_u = Q_b + Q_s. \tag{13}$$

Highest loading for Q_s occurs when:

- $c_a = 56.35\,\text{kN}\,\text{m}^{-2}$, $55.23\,\text{kN}\,\text{m}^{-2}$, $62\,\text{kN}\,\text{m}^{-2}$ and $62\,\text{kN}\,\text{m}^{-2}$,
- $Q_u = Q_b + Q_{s\ \text{a,b,c,d}} = 869.13 + (1\,897.02)$ $= 2\,766.15\,\text{kN}$,
- $Q_a = \frac{Q_u}{F_s} = \frac{2\,766.15}{3} = 922.05\,\text{kN}$.

Pile Load Test Results [kN]		**Static Equation Result [kN]**		
Case Nos. [24]	**Field test results [24]**	**Ultimate Adhesion**	$c_a = 0.4C_u$	$c_a = 0.3C_u$
Case 10	2 038.10	1 858.20	1 906.95	1 520.85
Case 11	3 782.50	2 876.09	3 490.47	2 879.72
Case 15	1 246.00	1 472.73	1 298.10	1 104.60
Case 16	4 761.50	5 694.00	5 520.08	5 327.40
Case 17	2 848.00	2 766.15	2 649.88	2 204.75
Case 21	6 354.60	5 507.28	4 555.90	3 782.03
Case 22	4 788.20	4 446.05	3 649.63	2 992.44
Case 23	5 375.60	4 624.07	3 821.75	3 117.03
Case 30	4 120.70	4 418.26	4 109.11	3 751.76
Case 31	756.50	1 282.18	982.46	823.77
Case 32	2 118.20	2 269.70	2 058.22	1 871.60
Case 33	2 589.90	2 612.48	2 308.86	2 064.55
Case 34	1 539.70	1 727.04	1 421.51	1 193.78
Case 35	2 429.70	2 215.64	1 870.80	1 549.05
Case 36	2 314.00	3 024.61	2 816.04	2 284.47
Case 37	2 750.10	3 676.83	3 295.71	3 093.92
Case 38	4 806.00	5 285.26	4 888.44	4 433.14
Case 39	3 506.60	3 503.05	3 049.40	2 525.02
Case 40	5 963.00	5 484.06	5 105.62	4 668.19
Case 41	5 874.00	6 421.12	5 894.22	5 358.85

TABLE 6. Static equation results including field test results for comparison.

5. SUMMARY OF RESULTS AND DISCUSSION

5.1. RESULTS

The results obtained from the estimation of ultimate loads from the static equations from the twenty boreholes are compared to the ultimate pile load test and shown below in Table 6. For the estimated ultimate loads, 11 out of 20 cases had a difference of 10 % or less from the load test, meaning majority of the cases gave close results relative to the pile load test. The ultimate load values presented from the field test cases and the values estimated using the tangent method are shown in Table 7.

The results are shown in Figures 4–6. On the basis of these figures, it is clear that the ultimate bearing capacities of the static equation, with respect to the adhesion ($c_a = 0.3C_u$, $0.4C_u$ & ultimate adhesion (Table 1)) used for skin resistance calculation, gives a relatively accurate prediction of the pile capacity.

Reference	**Pile load test (Q_u) [kN]**	**Tangent method (Q_u) [kN]**
Case 10	2 038.10	2 038.10
Case 11	3 782.50	3 782.50
Case 15	1 246.00	1 112.50
Case 16	4 761.50	3 204.00
Case 17	2 848.00	2 661.10
Case 21	6 354.60	5 162.00
Case 22	4 788.20	3 649.00
Case 23	5 375.60	4 183.00
Case 30	4 120.70	4 049.50
Case 31	756.50	756.50
Case 32	2 118.20	2 118.20
Case 33	2 589.90	2 358.50
Case 34	1 539.70	1 557.50
Case 35	2 429.70	2 447.50
Case 36	2 314.00	2 447.50
Case 37	2 750.10	2 759.00
Case 38	4 806.00	4 547.90
Case 39	3 506.60	3 506.60
Case 40	5 963.00	6 096.50
Case 41	5 874.00	5 927.40

TABLE 7. Ultimate load results of pile load tests and Tangent method.

The plots in Figures 4–6 show a linear correlation between the pile load test results and the static equation estimates. For the first case ($c_a = 0.3C_u$), a study of the linear regression line indicates that the static equation tends to slightly underestimate the ultimate pile capacity compared to the pile load test results. The linear correlation coefficient of 0.880 indicates a very high correlation strength. For the second case ($c_a = 0.4C_u$), the linear regression line indicates that the static equation also slightly underestimates the ultimate pile capacity as compared to the pile load test results, but the difference is smaller than in case 1. However, the linear correlation coefficient of 0.921 is higher than in Case 1, indicating an even stronger correlation strength. Lastly, for the third case using c_a as the ultimate adhesion value from Table 1, the linear regression line indicates that the static equation also slightly underestimates the ultimate pile capacity as compared to the pile load test results, but the difference is even smaller than in the other two cases. This

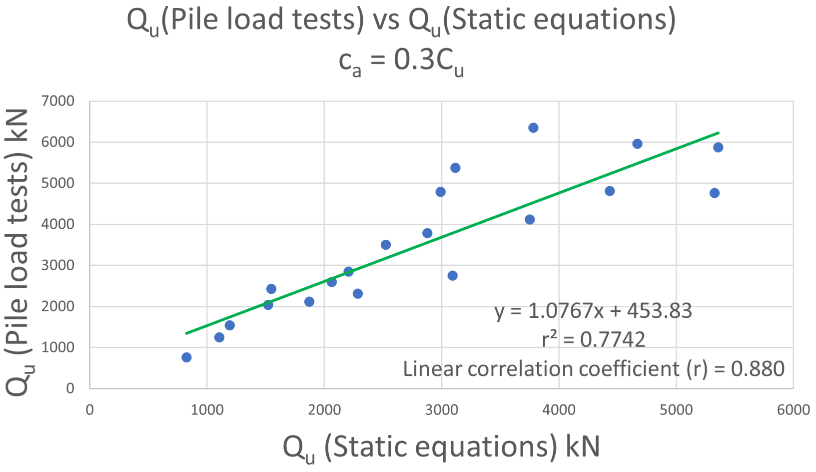

Figure 4. Plot of ultimate load: pile load tests vs static equations, when $c_a = 0.3C_u$.

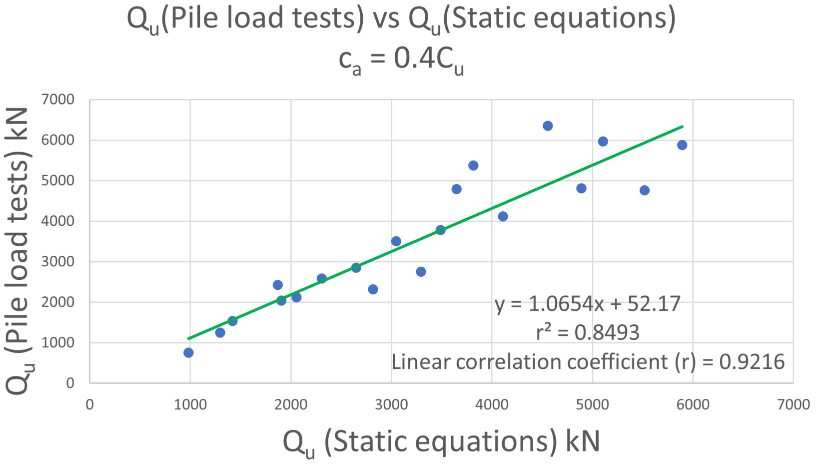

Figure 5. Plot of ultimate load: pile load tests vs static equations, when $c_a = 0.4C_u$.

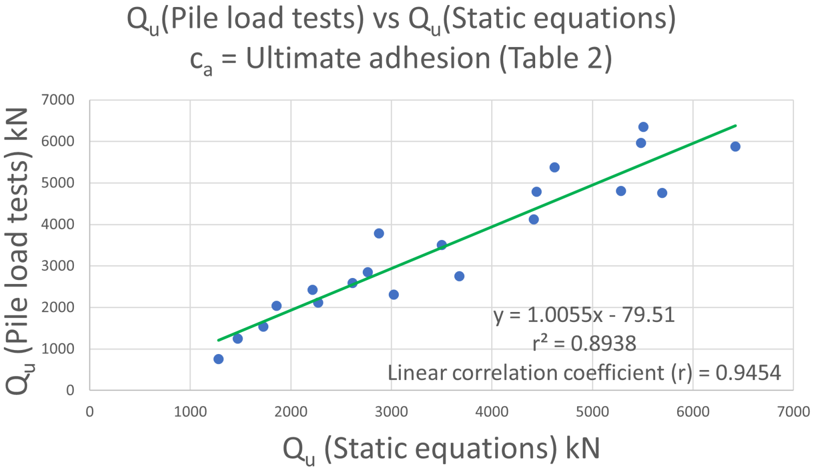

Figure 6. Plot of ultimate load: pile load tests vs static equations, when c_a = ultimate adhesion (Table 1).

case shows the highest linear correlation coefficient of 0.945, showing the strongest correlation strength between the three cases.

Figure 7 shows a linear correlation between the results of the pile load test and the Tangent method. The Tangent method involves drawing a tangent line at the beginning and end of the load-settlement curve to provide a reliable estimate of the ultimate load capacity of the pile. It is particularly useful for piles in clay soils where the load-settlement behaviour is non-linear and the pile's resistance to load increases significantly as the load approaches the ultimate capacity [28]. Based on the linear correlation coefficient ($r = 0.9528$) obtained from the plot, the tangent method can be said to have one of the strongest correlations with the pile load tests. The high correlation

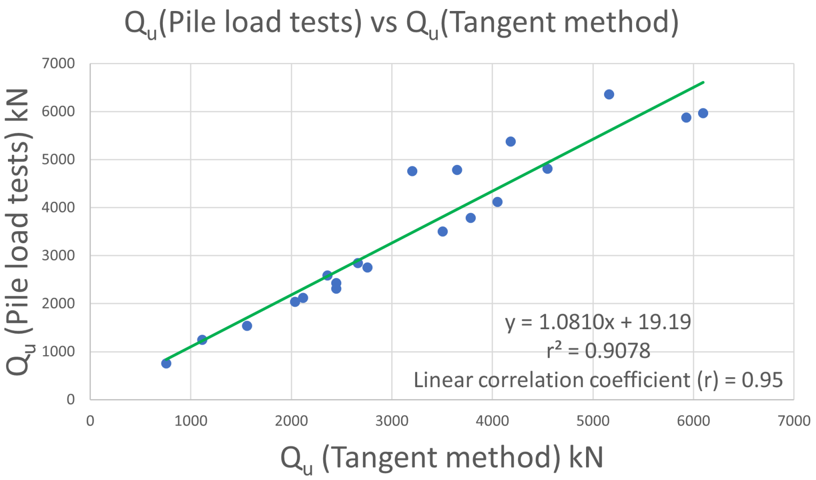

Figure 7. Plot of ultimate load: pile load tests vs tangent method.

Case	**Length [m]**	**Diameter [m]**	C_u **Base [kN m^{-2}]**	C_u **Skin [kN m^{-2}]**	**Ultimate adhesion**	$c_a = 0.4C_u$	$c_a = 0.3C_u$
10	23.99	0.52	191.6	98.48	1 858.20	1 906.95	1 520.85
11	12.81	0.76	258.66	199.52	2 876.09	3 490.47	2 879.72
15	7.05	0.76	129.33	114.96	1 472.73	1 298.10	1 104.60
16	7.02	0.76	129.33	114.96	5 694.00	5 520.08	5 327.40
17	13.73	0.76	214.6	135.74	2 766.15	2 649.88	2 204.75
21	25.01	1.20	143.7	82.01	5 507.28	4 555.90	3 782.03
22	25.28	1.00	143.7	82.67	4 446.05	3 649.63	2 992.44
23	26.02	1.00	143.7	84.42	4 624.07	3 821.75	3 117.03
30	12.20	0.79	134.12	116.4	4 418.26	4 109.11	3 751.76
31	9.30	0.63	124.54	86.22	1 282.18	982.46	823.77
32	9.24	0.63	124.54	102.03	2 269.70	2 058.22	1 871.60
33	12.17	0.62	126.46	102.99	2 612.48	2 308.86	2 064.55
34	9.40	0.77	120.71	100.11	1 727.04	1 421.51	1 193.78
35	12.23	0.77	137.95	108.73	2 215.64	1 870.80	1 549.05
36	15.22	0.80	153.28	138.91	3 024.61	2 816.04	2 284.47
37	9.55	0.77	124.54	86.22	3 676.83	3 295.71	3 093.92
38	16.01	0.77	153.28	116.40	5 285.26	4 888.44	4 433.14
39	15.25	0.94	153.28	116.40	3 503.05	3 049.40	2 525.02
40	12.72	0.94	141.78	116.40	5 484.06	5 105.62	4 668.19
41	16.26	0.94	153.28	111.50	6 421.12	5 894.22	5 358.85

Table 8. Dataset for sensitivity analysis.

suggests that the Tangent method provides a very reliable and consistent estimates of the pile bearing capacity.

A sensitivity analysis was considered noteworthy and is done. The cosine amplitude method determines the sensitivity of input parameters (soil and pile properties). The following equation represents the cosine amplitude method [29]:

$$S_s = \frac{\sum_{k=1}^{j} (X_{ik} * Y_{ik})}{\sqrt{\sum_{k=1}^{j} X_{ik}^2 \sum_{k=1}^{j} Y_{ik}^2}}, \qquad (14)$$

where X_i and Y_i are the input and output parameters, respectively. Sensitivity S_s explains how much the input and output parameters are related, with a sensitivity value of 0 being no relation and 1 a very strong relation. Python programming language running on Jupyter Notebook 7.0.8 [30] was used to automate the analysis. Table 8 shows all the variables used with the estimated ultimate loads being the output. The cases number is just an index and is not used in the analysis. The length, diameter, and cohesion values constitute the input variables. The side cohesion values were a weighted average of all the cohesion values across the pile length for a given pile.

5.2. Discussion

Comparing field pile load tests with theoretical static equations using soil parameters provides important information about the accuracy and usefulness of static equations in estimating pile bearing capacity. In this research, a total of 20 cases were examined and the

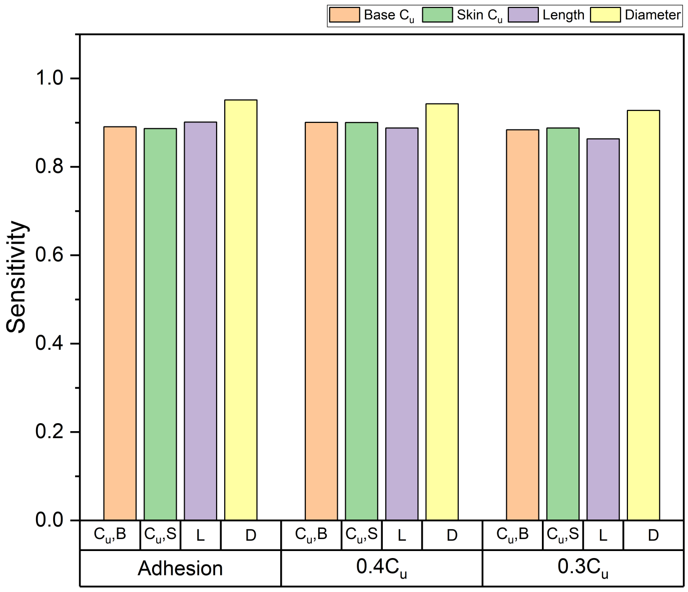

Figure 8. Sensitivity analysis results.

ultimate loads for each case were determined using static equations that relied on various adhesion values, specifically $0.3C_u$, $0.4C_u$, and an ultimate adhesion value, as shown in Table 1. These calculated ultimate loads were later compared to actual pile load tests results. The results show different levels of agreement between the ultimate loads calculated using the static equations and the values obtained from the pile load tests. This contrasts with the idea that only a few studies that presented adhesion factor formulations have shown a certain agreement in numerical and/or methodological terms [31]. When the ultimate adhesion value in Table 1 was used, the static equations tended to give the most accurate estimates when compared to the pile load test results. However, it is important to note that the static equations generally underestimated the pile capacity when the regression lines were used instead of the individual points. Though there are some differences noticed, the linear regression/correlation analysis shows that there is a positive correlation between the ultimate loads calculated from static equations and the values obtained from the pile load test. The strong correlation coefficients, especially when using the ultimate adhesion value in the static equation results, indicate a solid relationship between these two sets of data. In real-life situations, this study has clearly shown that static equations can be a very useful way to estimate the capacity of piles. In Figure 6 for instance, if the static equations give Qu to be 3 000 kN, the results show that Qu for the pile loading test is likely going to be around 3 000 kN. The designer then applies their necessary factor of safety to obtain the design load. However, it is important to validate this estimation method with more field results. Al-Atroush et al. [32] equally suggested their modified static equation method based on the classical Meyerhof approach needs further validation. Their approach aimed to estimate the ultimate pile bearing capacity of large-diameter bored piles using full-scale tests to failure. The conclusion based on static equations (Briaud, Meyehof, Decourt, Shoi & Fukui) in the study by Ningrum et al. [33] was the basis for determining the number of pile foundations used in a reservoir construction design. They based the reservoir design on the lowest pile bearing capacity value estimated, which is the Briaud's method.

Additionally, we can also recognise the Tangent method as a very reliable way to determine the ultimate pile capacity. It is simple to apply and does not require complex calculations. The Tangent method equally yielded reliable results in the work of Zhou et al. [34] as it was very close to bearing capacity estimation using the De Beer's method. It is a widely used and accepted approach, hence making it a practical alternative to the static equation. The findings of this study strongly embrace its usage, recommending it as one of the preferred methods based on the results obtained.

This study also shows that static equations are highly dependent on good laboratory and field tests in order to accurately determine the soil properties. That is why it is advisable to use static equations as an initial assessment tool, but also conduct field load tests to confirm their accuracy. To make static equation predictions more accurate, researchers should conduct additional studies to improve the soil parameter estimations. This can involve a thorough analysis of soil properties to gain a better understanding of the conditions. Furthermore, considering the impact of pile installation methods and construction techniques on pile behaviour could greatly improve the practical applications of static equations. Based on the above findings and discussion, it is strongly recommended to use the theoretical static equations to calculate the ultimate capacity in cohesive soils.

From Figure 8, it can clearly be seen that all the input parameters have a strong influence ($S_s > 0.86$) on the estimated ultimate bearing capacity, based on the static equations used in this study.

6. CONCLUSION

The main aim of the study presented in this paper was to evaluate the accuracy of static equations in estimating the bearing capacity of pile foundations by comparing their results with actual field pile load tests. The research analysed twenty different real cases involving bored piles in cohesive soil. The pile load capacities were calculated using static equations with various adhesion values, and these were then compared with the results obtained from field pile load tests.

The findings revealed that the static equations generally exhibited a strong correlation with the ultimate pile capacity from the pile load test results. However, the extent of the underestimation depended on the adhesion value used in the static equations. The use of the ultimate adhesion value from Table 1 showed the strongest correlation and provided the most accurate predictions, closely matching the pile load test results. The linear regression and correlation analyses demonstrated a positive correlation between the estimated and the measured ultimate loads. The strong correlation coefficients (r) of 0.95 show a solid correlation between these two sets of data. Also, the Tangent method remains one of the most reliable and consistent approaches for determining the ultimate pile bearing capacity based on the obtained results. This study strongly recommends static equations as a good estimate of pile capacity for cohesive soils. It also suggests that static equations could be more practical by improving how we estimate soil parameters and by considering pile installation and construction methods. It is strongly noted that in this study, static equations were only correlated with static load test results. Therefore, these findings should only be applied to the control and calibration of pile design methods as every site presents specific conditions that require the utmost caution and professional guidance.

Based on the preceding studies and the findings in this paper, the following recommendations are proposed:

- Thorough site-specific soil investigations and lab testing are important for better accuracy of static equations. This helps to gather reliable soil parameters for accurately predicting the pile bearing capacity.
- This study shows that the adhesion value chosen for static equations greatly affects the accuracy of the predicted pile bearing capacity. To improve reliability, further research into selecting the optimal adhesion value is recommended.
- Although the static equations currently used in this study provide reasonable estimates of pile bearing capacity, there is still room for improvement. Further research is recommended to develop and validate better static equation models for more accurate predictions of pile load capacity.
- This study indicates that using the ultimate adhesive value from Table 1 results in a correlation coefficient (r) of 0.95. This method showed the strongest correlation and provided the most accurate predictions closely matching the pile load test results. It is recommended that this method be adopted as a standard practice in pile foundation design.

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