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(Research Article)

Evaluation of pile capacity estimation methods in Bangladesh: A comparative study using static analysis and load tests

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Abstract

This research examines the accuracy and reliability of different theoretical and semiempirical methods to estimate the ultimate axial capacity of piles in Bangladesh, particularly for precast driven piles and cast-in-situ bored piles. By comparing predicted capacities with various methods, i.e., Meyerhof (1976), API RP 2A (1993), Tomlinson (1994), Norwegian Pile Guideline (2005), and Indian Standard (2010) for driven piles and Meyerhof (1976), NAVFAC DM 7.2 (1984), AASHTO (1986), O'Neill and Reese (1988), and Decourt (1995) for bored piles with actual measured capacities from static load tests, this study employs sub-soil investigation reports and pile load test results of 22 projects from around the country. The study employs various statistical parameters such as regression, coefficient of determination (COD), arithmetic mean, standard deviation, and cumulative probability to make a comparison among these methods. The study identifies that the most accurate estimates for driven piles are given by Tomlinson (1994) and API (1993), while Meyerhof (1976) and AASHTO (1986) are best suited for bored piles. In addition, the study indicates correlations between calculated and estimated capacities and offers suggestions for enhancing pile design procedures in Bangladesh's soft ground conditions.

Keywords: Pile capacity; Static analysis; Load tests; Driven piles; Bored piles; Bangladesh soils

1. Introduction

Piles are fundamental structural elements that are designed to distribute the loads of the superstructure to the more capable underlying soils at larger depths, particularly where there are high concentrations of soft soils at shallow depths like in Bangladesh. Accurate determination of pile capacity is important for ensuring structural safety as well as economic economy in foundation design. Traditional pile capacity determination methods include static load tests, dynamic testing, and static analysis based on soil mechanics principles. Yet, the intricacy of soil-pile behavior and local soil variability usually make theoretical expectations incompatible with reality, and field tests must be used to validate them.

Pile capacity has been estimated using empirical and theoretical advancements. Meyerhof (1956) [10] and Meyerhof (1976) [1] were among the initial methods, which calibrated the Standard Penetration Test (SPT) values against pile capacity with emphasis on skin friction and end bearing components. For cohesive soils, Meyerhof (1976) [1] proposed an adhesion factor, α, to adjust undrained shear strength, and for cohesionless soils, bearing capacity factors were connected with soil friction angles. The American Petroleum Institute (API) (1993) [2] formulated more sophisticated static analysis of offshore piles, later extended onshore, for large-diameter steel piles. Tomlinson (1994) [3] enhanced adhesion factor models for pile installation effects in cohesive soils, while Norwegian Pile Guideline (2005) [4] and Indian Standard (2010) [5] introduced regional empirical corrections.

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For bored piles, NAVFAC (1984) [6] and AASHTO (1986) [7] published guidelines based on soil disturbance and settlement, respectively. O'Neill and Reese (1988) [8] suggested methods accounting for effective stress and geometry of the pile, whereas Decourt (1995) [9] used rather extensive SPT-based empirical correlations. Static load tests as standardized by ASTM D1143[11] remain the benchmark for capacity validation, with design bounds such as Davisson's Offset Limit Load providing conservative approximations.

In Bangladesh, there are commonly soft compressible soils, and they pose particular difficulties to foundation engineering. The driven piles are widely accepted due to the quality of construction and confirmation of capacity at installation, while bored piles are handy in deeper soil layers. This investigation aims to compare the performance of selected static analysis methods with static load test results on 30 piles (15 precast driven and 15 cast-in-situ bored) on different projects between 1997 and 2018. It has threefold objectives: (1) to contrast theoretical ultimate capacities with load test results, (2) to assess semi-empirical methods for both piles, and (3) to establish relations between calculated and tested capacities.

2. Methodology

2.1. Data Collection

Sub-soil investigation reports and pile load test results were collected from 22 projects across Bangladesh, conducted between 1997 and 2018. These projects, funded by organizations such as the Public Works Department (PWD), RAJUK, and Dhaka Mass Transit Company (MRT), included 15 precast driven piles (PTP) and 15 cast-in-situ bored piles (CTP). Approximately 70% of the tests were supervised by the Department of Civil Engineering, BUET, with the rest done by Icon Engineering Services, Dhaka. Geographical locations are mentioned in Figure -1

2.2. Soil Modeling

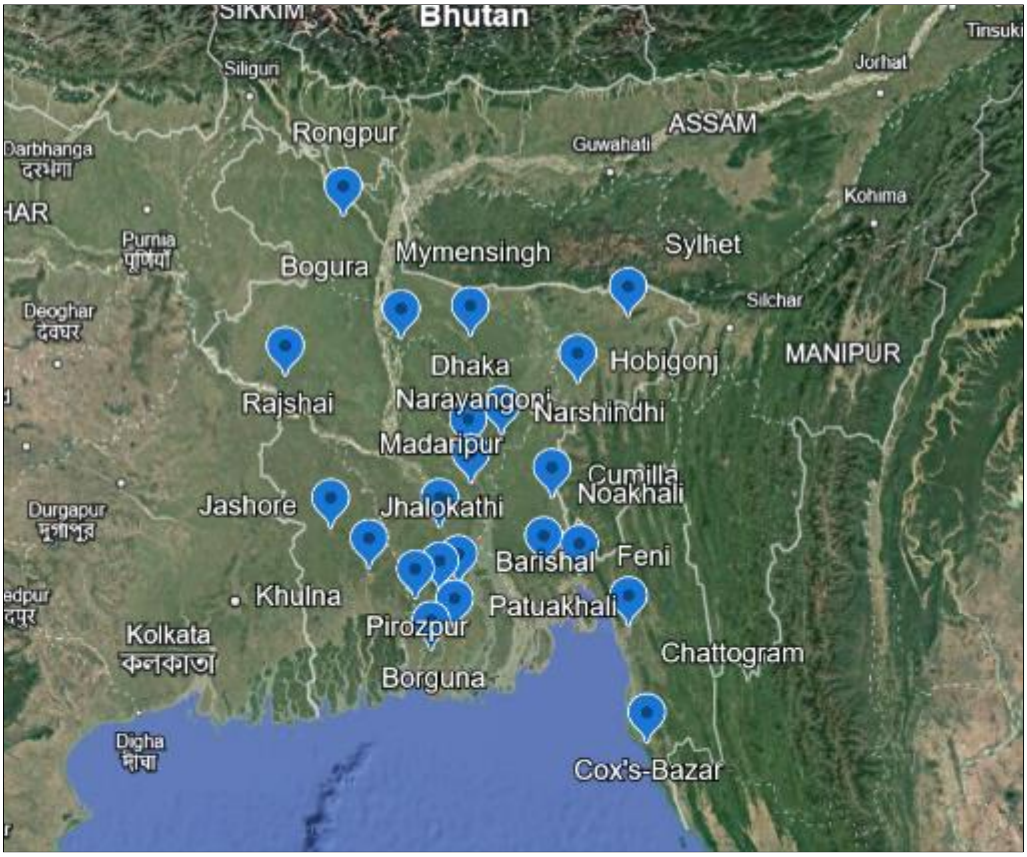

Figure 1 Geographical locations of the projects (Courtesy: Google Earth)

Soil strata in the study zones were defined by layered deposits typical of deltaic settings and considerable variations in soil type and properties with depth. The upper layers, up to approximately 5-10 meters, were primarily composed of soft to medium stiff clays and silts with high plasticity and low shear strength (c_u<25 kPa). These layers were adverse to shallow foundations due to high compressibility and low bearing capacity. Below these levels, the soil transformed into harder clays, dense silty sands, and local sand zones in another type of soil, with larger SPT N-values indicating higher strength and stiffness. Loose to medium-dense sands existed at depths of 15-30 meters in some locations, particularly riverine and coastal regions, providing improved end-bearing conditions to deep foundations. Idealization of the ground layers was done from borehole logs, and SPT N-values were used to estimate soil parameters such as undrained shear strength (cu) for clays and friction angle (ϕ) for sands, based on empirical formulas by Bowles (1977) [12] and Meyerhof (1956) [10] have been used.

2.3. Pile Capacity Estimation

2.3.1. Static Analysis

For driven and bored piles, ultimate capacity (Q_{ult}) is given by:

$$Q_{ult} = Q_s + Q_p = f_s A_s + q_p A_p$$

where

Q_s is total shaft friction and Q_p is total end bearing. The methods considered include:

Driven Pile Cohesive Soil

- Meyerhof (1976): $f_s = \alpha c_u$, $q_p = 9 c_u$
- API (1993): $f_s = c$, $q_p = 9 c$
- Tomlinson (1994): $f_s = \alpha c$, $q_p = 9 c$
- Norwegian Guideline (2005): $f_s = \beta P$, $q_p = 9 c$
- Indian Standard (2010): $f_s = \Sigma (\alpha_i ci)$, $q_p = 9 c$

Driven Pile Cohesionless Soil

- Meyerhof (1976): $f_s = K_s \tan(\varphi) \sigma_v$, $q_p = Nq \sigma_v$
- API (1993): $f_s = K_s \sigma_v \tan(\delta)$, $q_p = Nq \sigma_v$
- Tomlinson (1994): $f_s = 0.5 K_s \sigma_v \tan(\delta)$, $q_p = Nq \sigma_v$
- Norwegian Guideline (2005): $f_s = K_s \sigma_v \tan(\delta)$, $q_p = Nq \sigma_v$
- Indian Standard (2010): $f_s = \Sigma (K_i \sigma_{vi} \tan(\delta_i))$, $q_p = (1/2) D\gamma N\gamma + \sigma_v Nq$

Bored Pile Cohesive Soil

- Meyerhof (1976): $f_s = \alpha c_u$, $q_p = 9 c_u Nq$
- NAVFAC DM 7.2 (1984): $f_s = \sigma'_v K \tan(\delta)$, $q_p = Ncs c$
- AASHTO (1986): $f_s = \alpha c_u$, $q_p = Nc c_u b$
- O'Neill and Reese (1988): $f_s = \sigma'_v K \tan(\delta)$, $q_p = Nc S_u$
- Decourt (1995): $f_s = \alpha (2.8 N_s + 10)$, $q_p = K_p N_p$

Bored Pile Cohesionless Soil

- Meyerhof (1976): $f_s = N/100$ ($\leq$ 0.5 tsf), $q_p = 0.133 \eta N D B$
- NAVFAC DM 7.2: $f_s = K_s \sigma'_v \tan(\delta)$, $q_p = \sigma't Nq$
- AASHTO (1986): $f_s = K_s\sigma'_v \tan(\delta)$, $q_p = (1/3)(Nq \sigma'_v)$
- O'Neill and Reese (1988): $f_s = K_s \sigma'_v \tan(\delta)$, $q_p = Nq \sigma'_v$
- Decourt (1995): $f_s = \alpha (2.8 N_s + 10)$, $q_p = K_p N_p$

2.3.2. Load Tests

Static load tests followed ASTM D1143 (2007) [11], with loads applied up to 200–300% of design capacity. Ultimate capacity was determined using Davisson's Offset Limit Load:

$$S_{rl} = S + (3.81 + 0.008 D)$$

where S_{rl} is pile head movement (mm), S is elastic deformation, and D is pile diameter (mm). Extrapolation of load-settlement curves was employed for non-failure cases.

2.3.3. Statistical Analysis

Accuracy was evaluated using the Rank Index (RI)

$$RI = R_1 + R_2 + R_3 + R_4 + R_5$$

where R_1 is based on COD

$$COD = 1 - (\Sigma (Q_m - Q_p)^2) / (\Sigma (Q_m - Q_{m,mean})^2)$$

R_2 and R_3 use mean (μ) and standard deviation (σ) of Q_p/Q_m, and R_4 and R_5 evolve from cumulative probability at 50% and 90%. Lower RI indicates higher precision. The average error was estimated as:

$$E_{ave} = (Q_p / Q_m)_{50\%} - 1$$

3. Results

3.1. Pile Capacity Predictions

Predicted capacities for 15 PTP (Precast Test Pile) and 15 CTP (Cast-in-Situ Test Pile) were computed and compared with load test results (Figures 2 and 3). For PTP, lengths ranged from 7 to 30.5 m with diameters of 0.3–1 m. For CTP, lengths were 20–65 m with diameters of 0.25–2 m.

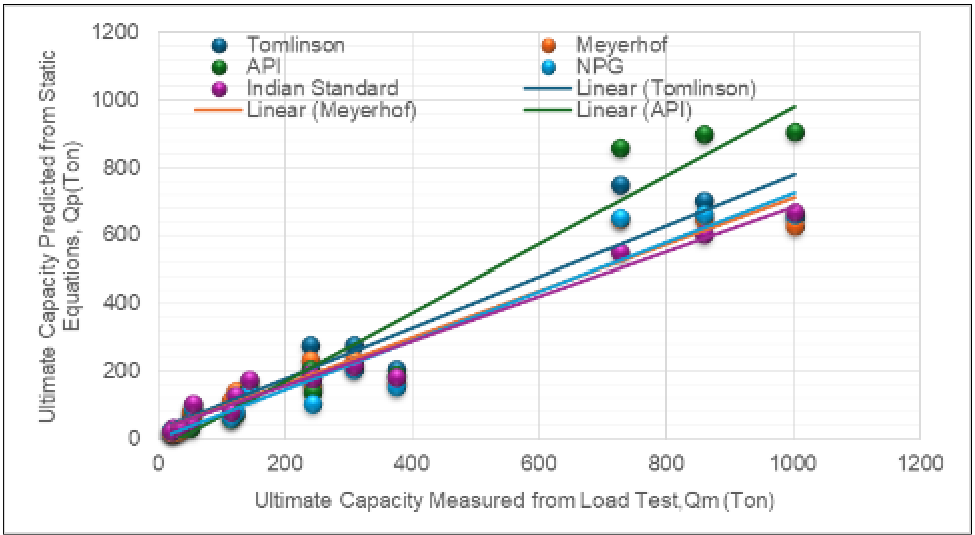

Figure 2 Correlation between Qp and Qm for PTP

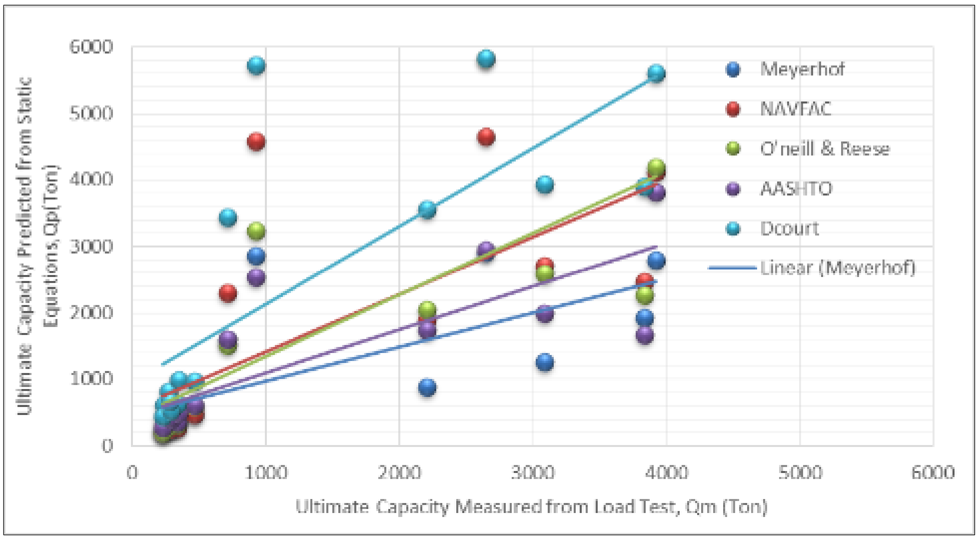

Figure 3 Correlation between Qp and Qm for CTP

Table 1 Statistical and probability analysis of PTP methods

Method	COD	R1	μ	R2	σ	R3	P50	R4	P90	R5	RI
Meyerhof (1976)	0.824	4	0.897	3	0.295	3	0.826	3	1.35	2	15
API (1993)	0.937	1	0.869	4	0.288	2	0.904	2	1.22	1	10
Tomlinson (1994)	0.868	2	1.011	1	0.118	1	1.032	1	1.50	5	10
Norwegian (2005)	0.827	3	0.847	5	0.329	4	0.769	5	1.45	4	21
Indian Standard (2010)	0.814	5	0.933	2	0.349	5	0.803	4	1.36	3	19

Table 2 Statistical and probability analysis of CTP methods

Method	COD	R1	μ	R2	σ	R3	P50	R4	P90	R5	RI
Meyerhof (1976)	0.468	2	1.166	1	0.711	2	1.026	1	2.50	3	9
NAVFAC (1984)	0.197	4	1.460	4	1.147	4	1.029	2	4.00	4	18
AASHTO (1986)	0.648	1	1.315	2	0.582	1	1.319	4	2.495	2	10
O'Neill and Reese (1988)	0.311	3	1.394	3	0.731	3	1.246	3	2.46	1	13
Decourt (1995)	0.725	5	2.480	5	1.376	5	2.092	5	5.30	5	25

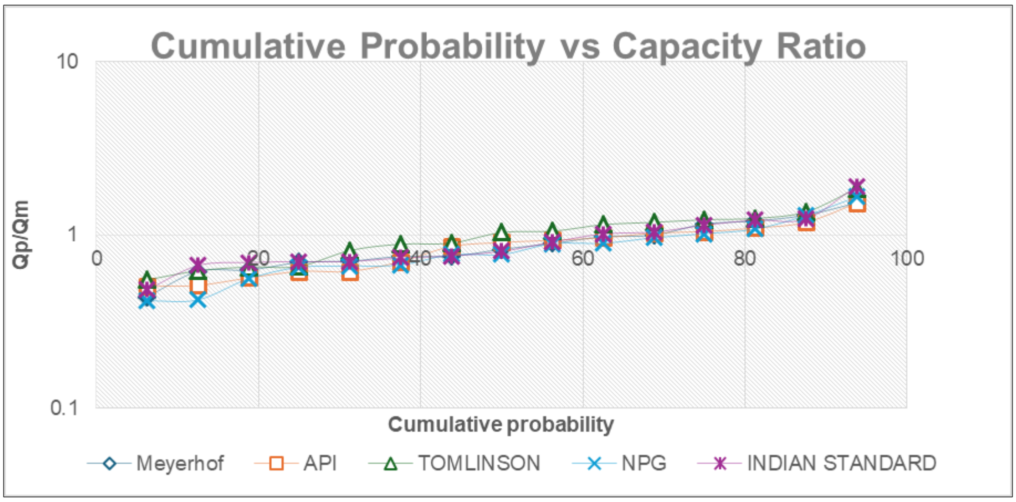

Figure 4 Cumulative probability vs. Qp/Qm for PTP

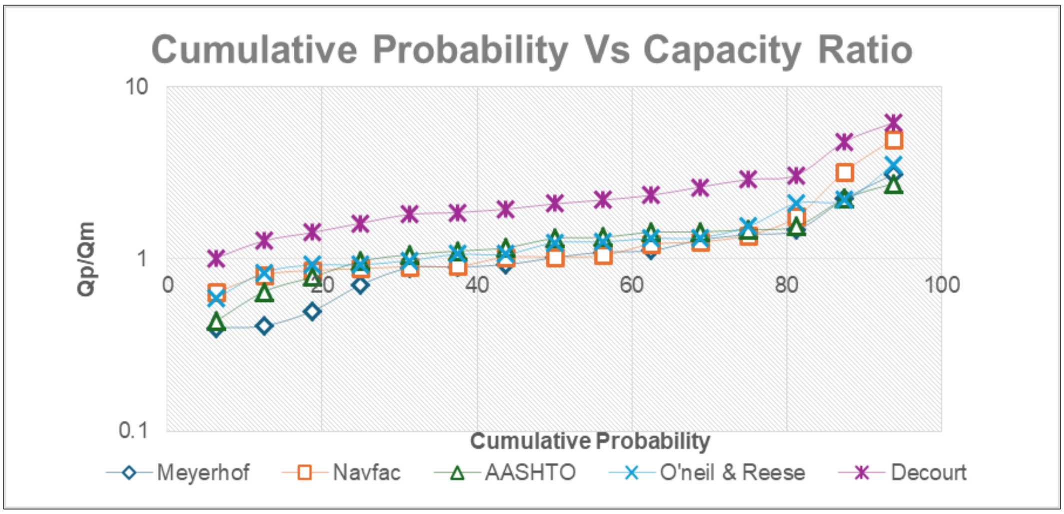

Figure 5 Cumulative probability vs. Qp/Qm for CTP

3.2. Statistical Insights

Statistical comparison (from Table-1 and Table-2) identified that the approaches varied greatly in predicting pile capacity for different pile types. In the case of precast driven piles (PTP), Tomlinson (1994) [3] was the most reliable, with the coefficient of determination (R2=0.919) to indicate the high correlation between estimated and measured capacities. Its Rank Index (RI = 10) was the least with minimal systematic error (μ=1.01) and low scatter (σ=0.34), evidenced by horizontal slope of cumulative probability plot (Figure 4). Norwegian Pile Guideline (2005) [4] had the maximum RI (21) along with extremely high underestimation (μ=0.847) and increased scatter (σ=0.329).

For cast-in-situ bored piles (CTP), Meyerhof (1976) [1] performed best with lowest RI (9) and moderate R2 (0.487). Despite the lower R2, its slight overestimation (μ=1.166), good spread (σ=0.711), and flat probability curve at aggregated level (Figure-5) indicate its suitability. AASHTO's method (1986) [7], though second best (RI = 10), suffered higher overestimation (μ=1.315).

4. Discussion

For PTP, the Tomlinson (1994) [3] method was favored with equal adhesion and end-bearing modifications, while API (1993) [2] applied effective stress without restrictive conditions but restricted the maximum value of end-bearing and side friction such that it does not produce unsafe capacities. Meyerhof (1976) [1]is conservative due to restrictive critical depth limitations. For CTP, Meyerhof (1976) [1] has good correspondence to SPT values while AASHTO (1986) [7] removes the depth effects, but overestimation still remains in the longer piles. Decourt (1995) [9] overestimates significantly due to uncorrected SPT values and the lack of limiting limits. In general, Precast piles were more accurate and reliable in capacities predictions for the different methods while bored piles overestimate the capacity significantly than the measured capacity for most of the methods. The reliability of theoretical methods decreases for bored piles due to soil disturbance effects and construction variabilities. Pile installation methods are key factors behind this. During pile driving, soil strength may increase due to pore water pressure dissipation, resulting in reduced settlement and improved capacity during practical load tests. Pile size and length also impact the prediction of capacities, with smaller size and shorter length piles providing more reliable values in both cases.

5. Conclusions

This research confirms that: Tomlinson (1994) [3] and API (1993) [2] provide the best driven pile estimates in Bangladesh, which are accompanied by errors of 3.2% and -9.6%, respectively. Meyerhof (1976) [1] and AASHTO (1986) [7] are most appropriate for bored piles, with the inaccuracies of 2.6% and 31.9% but adequate Factor of safety should be employed for design capacity. Correlations between the observed (Q_m) and predicted (Q_p) capacities are strong with high R^2 values near unity for top methods.

Recommendations

More research is recommended to study the impacts of pile driving methods on pile and base resistances as well as pile capacity. Using Chin's approach with static analysis to separate shaft and base resistances can offer more precise prediction.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

Neither author has any other financial or non-financial interests that could be perceived to influence the results or interpretation of this manuscript.

Statement of ethical approval

The present research work does not contain any studies performed on animals/humans' subjects by any of the authors.

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