APPLICABILITY OF THE EXISTING EMPIRICAL FORMULAS IN DETERMINING THE AXIAL LOAD CARRYING CAPACITY OF SINGLE PILES IN BANGLADESHI SOILS

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ABSTRACT

Piles are frequently used in Bangladesh for the construction of deep foundation. Determination of the appropriate axial load carrying capacity of a single pile is very important to ensure the safe and economic design of the structures. The load carrying capacity of pile can be estimated from various empirical formulas. However, their reliability and applicability may vary with the geographical regions and the soil types. This research aims to assess the reliability of globally recognized empirical formulas for estimating the load carrying capacity of axially loaded single piles in Bangladeshi soils. The pile load test data and the corresponding subsoil investigation reports have been collected from several construction projects all over the country to achieve the objectives. Fifteen precast piles and fifteen cast-in-situ piles data have been collected. In this study, three empirical formulas proposed by Meyerhof (1976), AASHTO (1986) and BNBC (2020) have been used for estimating the axial load carrying capacity of cast-in-situ single piles. Similarly, another three empirical formulas named Meyerhof (1976), Tomlinson (1994) and BNBC (2020) have been used for precast piles. The static pile load test result has been analyzed by Davisson method. It has been observed that Meyerhof (1976) formula provides the best correlation with the measured load test result both for cast-in-situ piles and precast piles. The authors believe that this research will recommend the basic empirical equations suitable for Bangladeshi soil conditions, thus the engineers can accurately predict the pile capacity, ensuring a safer and cost-effective foundation design.

Keywords: *Deep foundation, Load carrying capacity, Static load test, Axially loaded piles, Empirical formulas.*

1. INTRODUCTION

Piles are an essential structural component that transfer loads from the superstructure to the deeper earth layers, particularly in situations when shallow foundations are shown to be impracticable. Soft and loose soils are frequently observed in the shallower depths at different parts of Bangladesh because of its recent alluvial deposition and deltaic formation. Consequently, the pile foundations, for example, bored piles, precast piles, etc. are usually suggested for building foundation. Driven piles are widely used because of their superior quality and real-time on-site load assessment. On the other hand, the expansion of infrastructure including high-rise buildings and bridges has increased the use of large diameter cast-in-situ piles. It is still difficult, even for highly skilled geotechnical engineers, to estimate the load-carrying capacity of bored or in situ piles accurately. There are several conventional and empirical methods available for determining pile capacity, but choosing one needs a thorough understanding of the soil properties and the method's geographical applicability. Conventionally, static load testing is a standard procedure to determine the carrying capacity of a pile (Bowels, 1988). The American Petroleum Institute (API) provides a static analysis process intended for the use in offshore construction. The approach mainly addresses large-diameter open-ended steel pipe piles that are driven with an impact hammer to the point of final penetration (American Petroleum Institute 2003). Apart from this, the empirical methods provided by many researchers are mainly based on different soil types and conditions. In 1959, Meyerhof proposed a theoretical relationship between the ultimate axial capacity of driven piles and corrected standard penetration test results. Focusing on the behavior of the drilled cast-in-situ piles in granular soil, he also put up a formula in 1976 for calculating the piles' capacity. In order to account for the relationship between the rigidity modulus and the soil's angle of internal friction, Vesic (1977) updated Meyerhof's (1976) bearing capacity factor for the end bearing of both driven and drilled piles in granular soil. Tomlinson (1994) focused on the behavior of driven piles in cohesive soil, particularly on increasing adhesion, also referred to as the reduction factor, which was first suggested by Peck et al. (1974).

Several research works have been carried out in Bangladesh to assess the applicability of different empirical formulas in perspective of Bangladesh. Sadek (1989) studied pile load tests on the bored pile at three different sites of Dhaka city and compared them with the existing theoretical results. The variables considered are critical depth, loosening effect of soil, and groundwater level. However, due to a lack of sufficient data, Sadek (1989) could not draw any correlation between theoretical results and the actual results from the pile load tests. Sandip Kumar, D (2020) carried out a study to compare some selected empirical equations used globally to estimate axial load carrying capacity of pile and compared their results with pile load test results collected from twenty- two projects all over the country. In this study it has been observed that the Tomlinson (1994), API (1993) and Meyerhof (1976) methods provide the most reliable and justified correlation between predicted and measured capacity for precast/ driven piles. On the other hand, for the cast in situ/ bored piles, AASHTO (1986) and O'Neill & Reese (1988) and NAVFAC DM 7.2 (1984) methods provide the most reliable and justified correlation between predicted and measured capacity.

The static pile load test is a time-consuming as well as an expensive method. Consequently, the most important step in any design process is to validate the suitability of chosen formulas in a particular soil condition using local correlations between the static resistance estimation and the load test results. Therefore, this study attempts to evaluate the rationality of an internationally accepted empirical method for calculating the load-carrying capacity of axially loaded single piles in the view of Bangladesh soils. The purpose of this research is to compare the axial load-carrying capacity of piles estimated using different empirical formulas with the actual pile load test results to check their reliability and applicability in the Bangladeshi soil conditions. The pile load test data and the corresponding subsoil investigation reports have been collected from several construction projects all over the country to achieve the objectives. Fifteen precast piles and fifteen cast-in-situ piles data have been collected. Finally, the estimated load carrying capacity of the axially loaded single pile obtained from three different empirical formulas are compared with the static load test results.

2. METHODOLOGY

A total thirty numbers of static pile load test data have been collected from several construction projects throughout the country. Among them, there are fifteen cast-in-situ pile data and fifteen precast pile data. The subsoil investigation report of the corresponding locations has been collected along with the pile test data. The geotechnical condition of the pile locations consists of both cohesive and cohesionless soils. Three different empirical formulas have been used to predict the ultimate load carrying capacity from the sub-soil investigation report. For precast piles, the Meyerhof (1976), the Tomlinson (1994) and the BNBC (2020) methods have been used for the capacity estimation of pile. Whereas, the Meyerhof (1976), the AASHTO (1986) and the BNBC (2020) formulas have been used for cast-in-situ piles. The ultimate pile capacity (Q_u) is calculated as the combination of the skin friction capacity of pile (Q_s) and the end bearing at the tip of the pile (Q_p). Afterwards, the estimated ultimate pile load capacity results from each formula have been compared with the corresponding measured value obtained from the pile load test by using Davisson's offset method.

2.1 Davisson's Offset Method

The Davisson's method (1972) defines the ultimate load at the point where the applied load exceeds the elastic compression of the pile by a specified value (0.15 inches) plus an additional factor accounting for soil movement ("soil quake"). This "soil quake" represents the deformation required to fully engage the soil strength beneath the pile tip. This method provides the lowest estimate of axial compression capacity directly from the load-settlement curve, eliminating the need for extrapolation. It assumes that capacity is reached at a small toe movement and estimates this movement based on the pile's stiffness (length and diameter). While primarily intended for quick testing of driven piles, Davisson's method requires loading near failure for accurate results.

2.2 Meyerhof (1976) Method for Precast Piles

The Meyerhof (1976) method provides a framework for estimating the axial capacity of precast piles both in cohesive and cohesionless soils. The proposed equations in case of cohesive soils are as follows;

$$Q_s = \dot{\alpha}.c_u.A_s \tag{1}$$

$$Q_p = 9.c_u.A_p \tag{2}$$

Where, Q_s is the skin friction capacity, $\dot{\alpha}$ is the adhesion coefficient, c_u is the undrained shear strength, A_s is the pile surface area, Q_p is the end bearing capacity, A_p is the cross-sectional area of pile tip. Besides, for cohesionless soils the related equations are:

$$Q_s = \beta.\sigma.(tan\delta).A_s \tag{3}$$

$$Q_p = N_c.\sigma.(tan\delta).A_p \tag{4}$$

Where, Q_s is the skin friction capacity, β is the adhesion factor depending on pile type and soil properties, σ is the effective overburden pressure, δ is the angle of internal friction, A_s is the pile surface area, N_c is the bearing capacity factor for end bearing in cohesionless soil, A_p is the tip area.

2.3 Tomlinson (1994) Method for Precast Piles

For cohesive soils, the proposed equation for the skin friction and the end bearing according to Tomlinson (1994) method are as follows:

$$Q_s = \beta.c_u.A_s \tag{5}$$

$$Q_p = N_c.c_u.A_p \tag{6}$$

Where, Q_s is the skin friction capacity, β is an adhesion factor with pile type and soil dependency, c_u is undrained shear strength of soil, A_s is the pile surface area, N_c is the bearing capacity factor, A_p is cross-sectional area of pile tip. Whereas, for cohesionless soils the equations are as follows;

$$Q_s = k.\sigma.(tan\delta)A_s \tag{7}$$

$$Q_p = N_c.\sigma.A_p \tag{8}$$

Where, k is a soil dependent coefficient, N_c is the bearing capacity factor for end bearing in cohesionless soil, δ is the angle of friction between pile and soil material.

2.4 BNBC (2020) Method for Precast Piles

The following equations are proposed in BNBC (2020) for cohesive soils.

$$q_s = 1.8\ \bar{N}_{60}\ (in\ kPa) \leq 70\ kPa \tag{9}$$

$$q_p = 45N_{60}\ (in\ kPa) \leq 4000\ kPa \tag{10}$$

Where, $\bar{N}_{60}$ is average N value over the pile shaft length and N_{60} is the N value at pile tip. The equations are as follows for cohesionless soils.

$$q_s = 2\ \bar{N}_{60}\ (in\ kPa) \leq 60\ kP \tag{11}$$

$$q_p = 40\ N_{60}\ \left(\frac{L}{D}\right) in\ kPa\ \leq 400\ N_{60}\ and\ \leq 11000\ kPa \tag{12}$$

Where, L is the length of the pile and D is the diameter of pile.

2.5 Meyerhof (1976) Method for Cast-in-situ Piles

Meyerhof (1976) method proposed some equations to estimate the ultimate load carrying capacity of single cast-in-situ piles both in cohesive and cohesionless soils. For cohesive soils the proposed equations are:

$$q_s = 0.36c_u \tag{13}$$

$$q_p = \frac{0.133\ \bar{\bar{N}}.D}{B}\ \leq q_1 \tag{14}$$

Where, q_s is the unit side resistance, c_u is the undrained shear strength, q_p is the unit base resistance, D is the depth drilled into granular bearing stratum in “ft”, B is the width or diameter of shaft in “ft”, q_1 is the limiting point resistance for cohesive soil.

For cohesionless soils,

$$q_s = \frac{N}{100} \leq 0.5\ \text{tsf} \tag{15}$$

Where, N is the standard penetration blow count along the shaft.

$$Q_p = \frac{C_N N}{100} A_p \quad (16)$$

Where, N is the standard penetration resistance (blows/ft).

2.6 AASHTO (1986) Method for Cast-in-situ Piles

AASHTO (1986) method also provides specific empirical formulas for estimating the ultimate load carrying capacity of axially loaded single piles. For cohesive soil,

$$q_{sz} = \dot{\alpha}_z . c_u \quad (17)$$

$$q_p = N_c . c_u \le q_p = 40\ tsf \quad (18)$$

Where, $\boldsymbol{N_c = 6.0\left[1 + 0.2\left(\frac{L}{B_b}\right)\right]}$, c_u is the average undrained shear strength of clay, q_{sz} is the unit skin friction at a depth "z", $\dot{\alpha}_z$ is an empirical factor that varies with depth, q_p is the unit end bearing capacity of pile, L is the penetration of the shaft, B_b is the diameter of the base of the shaft.

For cohesionless soil,

$$q_s = \beta . \sigma \le 2\ tsf \quad (20)$$

$$q_p = 0.6 N_{spt}\ tsf\ (for\ uncorrected\ N_{spt}\ value\ of\ 0{\sim}75) \quad (21)$$

$$q_p = 45\ tsf\ (for\ uncorrected\ N_{spt} value\ of\ above\ 75) \quad (22)$$

Where, β is the side resistance coefficient, σ is the vertical effective stress of soil at a certain depth, N_{spt} is the uncorrected field SPT N value.

2.7 BNBC (2020) Method for Cast-in-situ Piles

According to BNBC (2020) the proposed empirical equations to estimate the ultimate capacity of pile are as follows;
For cohesive soil,

$$q_s = 1.2\bar{\bar{N}}_{60}\ (in\ kPa) \le 70\ kPa \quad (23)$$

$$q_p = 25 N_{60}\ (in\ kPa) \le 4000\ kPa \quad (24)$$

Where, $\boldsymbol{\bar{\bar{N}}_{60}}$ is the average N value over the pile shaft length, N_{60} is the N value in the pile tip vicinity.

For cohesionless soil,

$$q_s = 0.09\bar{N}_{60}\ (in\ kPa) \le 60\ kPa \quad (25)$$

$$q_p = 15 N_{60} \frac{L}{D}\ (in\ kPa) \le 150 N_{60} \le 4000\ kPa \quad (26)$$

3. RESULT AND DISCUSSION

3.1 Load carrying capacity of Precast Piles

In this study, fifteen precast pile load test data have been considered for empirical analysis and static load test analysis. The pile data have been collected from different construction projects across the country. The Davisson's method has been used to estimate the ultimate load carrying capacity from the static pile load tests data. Meyerhof (1976), Tomlinson (1994), BNBC (2020) methods have been used for empirical analysis. Figure 1 represents the correlation between the ultimate capacity measured from load test data (Q_m) and the ultimate capacity estimated by using different empirical formulas (Q_e). The graphs indicate good correlation between measured capacity and estimated capacities for all empirical formulas here. Figure 2 represents the comparison between the ultimate capacities for all empirical formulas considered in this study and plotted it against the measured ultimate capacity from field test data. The graph indicates that the Tomlinson (1994) shows the best correlation with measured load tests. Therefore, the best suited regression equation for precast piles is obtained as $Q_m = 1.22*Q_e$ with R^2 value 0.986.

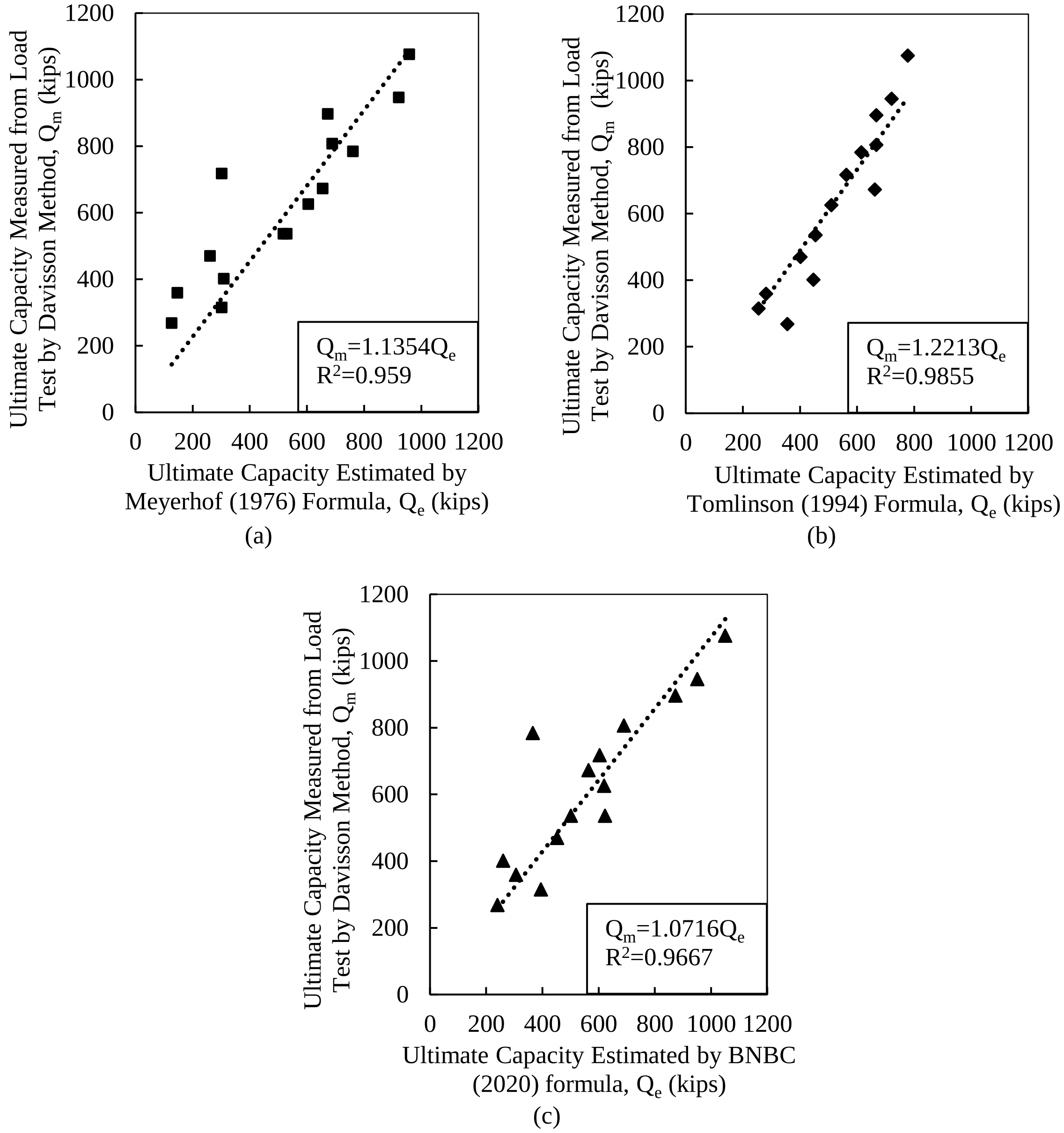


Figure 1: Correlation between Qm and Qe of precast pile by using; (a) Meyerhof (1976), (b) Tomlinson (1994) and (c) BNBC (2020) formulas.

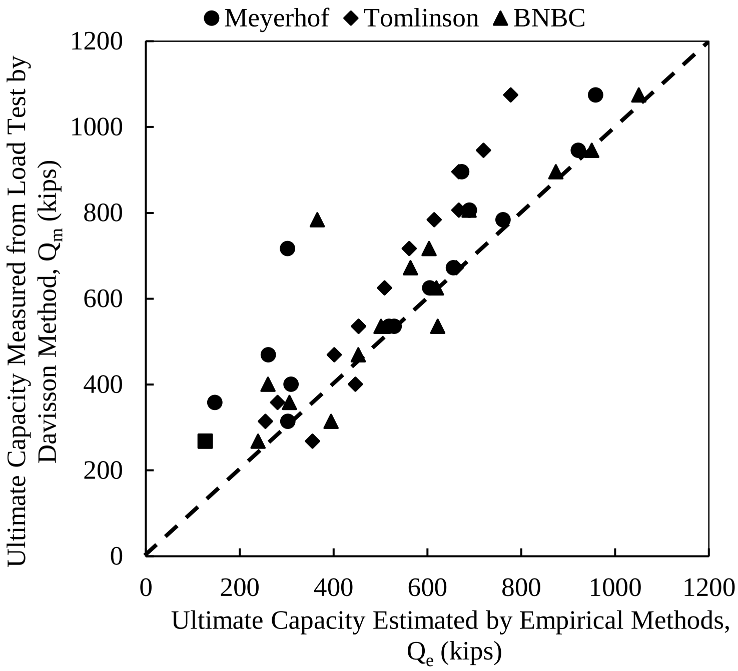
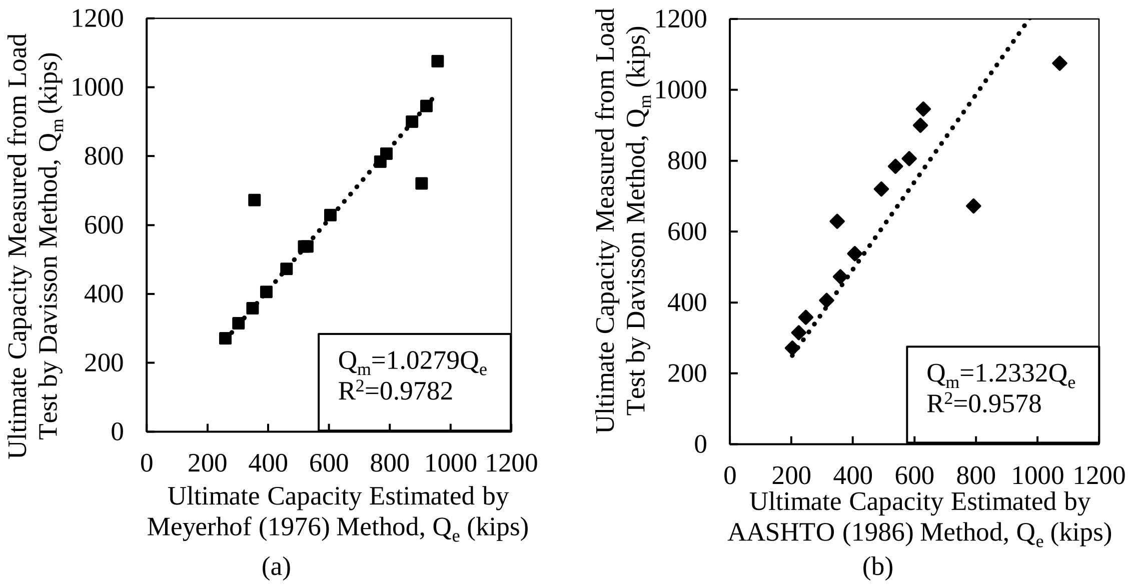
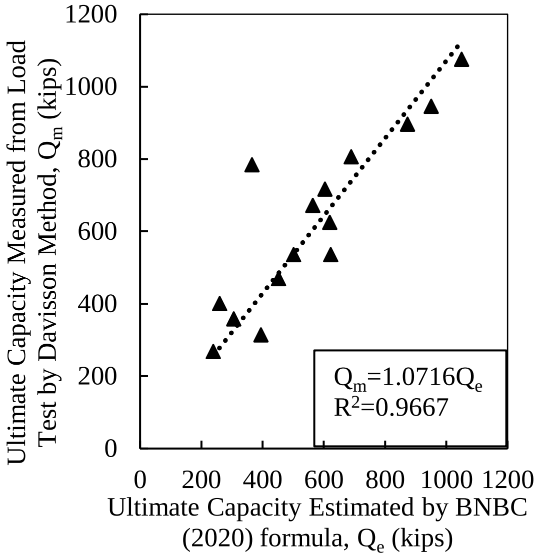


Figure 2: Comparison between Q_m and Q_e for precast piles by using Meyerhof (1976), Tomlinson (1994), and BNBC (2020) formulas.

3.2 Load carrying Capacity of Cast-in-situ Piles

In this study fifteen cast-in-situ pile test data have been considered for empirical analysis and static load test analysis. To estimate the ultimate load carrying capacity of static pile load tests data Davisson method has been used. Meyerhof (1976), AASHTO (1986), BNBC (2020) methods have been considered for empirical analysis.





(c)

Figure 1: Correlation between Q_m and Q_e of cast-in-situ piles by using; (a) Meyerhof (1976), (b) AASHTO (1986) and (c) BNBC (2020) formulas.

Figure 3 represents the correlation between ultimate capacity measured from load test data (Q_m) and ultimate capacity estimated by using different empirical formulas (Q_e). The graphs indicate good correlation between measured capacity and estimated capacities for all empirical formulas here.

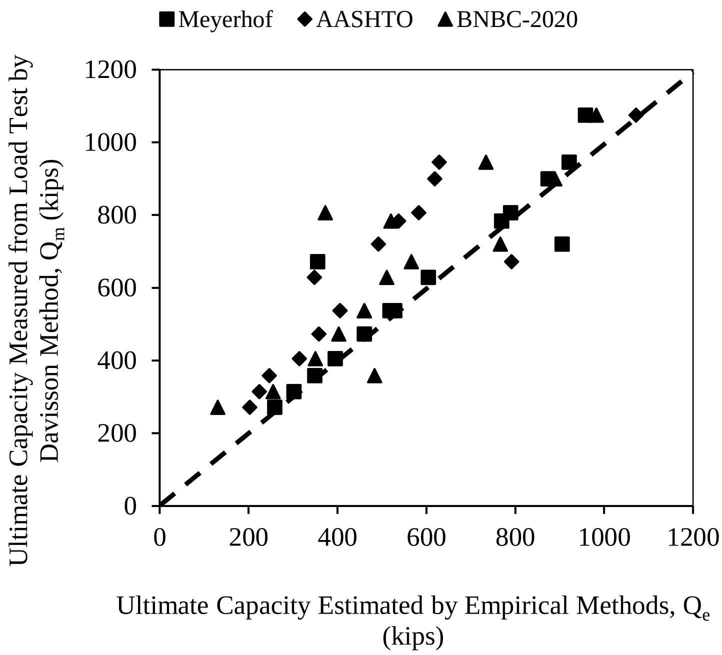


Figure 4: Comparison between Qm and Qe for cast-in-situ piles by using Meyerhof (1976), AASHTO (1986) and BNBC (2020) formulas.

Figure 4 represents the comparison between the ultimate capacities for all empirical formulas considered in this study and plotted it against the measured ultimate capacity from field test data. The graph indicates that the Meyerhof (1976) shows the best correlation with measured load tests. So, the best suited regression equation for precast piles is Q_m =1.0279Q_e with R^2=0.9782.

4. CONCLUSIONS

This research evaluated the applicability of various empirical formulas for estimating the axial load carrying capacity of single piles in Bangladeshi soils. For precast piles three empirical equations have been considered for estimating ultimate capacity of pile namely Meyerhof (1976), Tomlinson (1994), BNBC (2020) methods. The results obtained by empirical equations were plotted against the results measured from collected field static pile tests data. From the graphs, it is observed that Tomlinson (1994) formula provides considerably better consistency in predicting the load carrying capacity of precast piles.

Similarly, to check the applicability of empirical equations for cast-in-situ piles three empirical formulas have been chosen that are Meyerhof (1976), AASHTO (1986) and BNBC (2020) methods. It is observed from the graphs that the Meyerhof (1976) method provides better correlation with the measured capacity of cast-in-situ piles.

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