COMPARATIVE STUDY OF BNBC, GEO5, MEYERHOF, AND VARIOUS INTERPRETATION METHODS OF PILE LOAD TEST FOR DETERMINING THE ULTIMATE LOAD CAPACITY OF SINGLE PILES IN BANGLADESHI SOILS

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ABSTRACT

The performance of piles is crucial to ensure the stability of foundation systems, especially in Bangladesh, where soil conditions vary significantly. The focal point of this study is to calculate the ultimate load capacity of four single piles used in three water control structures in Bangladesh, constructed by the BWDB, with a particular focus on pile load test data and comparison with methods described in the BNBC, NAVFAC DM 7.2, and Meyerhof's theory. Pile load tests were done according to ASTM D1143-81 guideline and by following the BNBC guideline that suggests testing piles 1.5 to 2 times the percentage of the design load of the superstructure that a single pile has to carry. In these sluices, a very conservative design load is adopted. That's why, although a 1.5 times load is applied, the pile load test result didn't reach failure. Hence, the primary objective of this study was to extrapolate the ultimate load capacity of piles based on our available data using four different extrapolation methods which are Chin's Method, Brinch Hansen's 90% Criterion, Mazurkiewicz's Method, Vander Veen's Method and correlate the conclusions with predictions made by NAVFAC DM 7.2 which is carried out using Geo-5 software, BNBC 2020 and Meyerhof based on soil N-values. Here, from previous studies conducted in Bangladesh, it is found that Meyerhof gives the most accurate result for bored piles. Based on these studies, we have taken Meyerhof as a baseline and compared all the above stated methods with it. The observations from this study were that, among all the extrapolation methods, Van der Veen and Mazurkiewicz's Method gave the closest evaluations of ultimate load to Meyerhof. These methods showed the highest mean capacity ratio, which indicates high accuracy, but displayed the highest standard deviation due to their non-linear curve fitting function, indicating it is less reliable for consistent prediction. This demonstrates that these two methods are best suited where very limited data are available, tolerating the higher scatter for the benefit of a better average prediction. On the contrary, Chin's Method, Brinch Hansen's 90% Criterion showed a lower mean capacity ratio and standard deviation than the previously stated two methods. It indicates that, although they have low accuracy, they are more reliable for consistent prediction. Among the two empirical methods, NAVFAC DM 7.2 and BNBC 2020, both show significantly high accuracy, having a very high mean capacity ratio, whereas BNBC gives the most conservative estimate. The high accuracy of these two methods indicates that a field calibration factor can be applied to assist the designer in predicting the actual capacity of the pile. In addition, the structural capacity of all the piles used in these sluices is significantly high, which indicates that the pile will not fail structurally before taking the full geotechnically derived ultimate load. The findings provide useful insights for engineers in Bangladesh to adopt the most reliable method for determining pile load capacity when a load test is not done up to failure based on local soil conditions.

Keywords: *Load Capacity, load test, Geo-5, Meyerhof, BNBC.*

1. INTRODUCTION

Pile foundation is a vital element in structural design, especially in Bangladesh, where layers of soil are present because the surface soil cannot withstand the load of the structure owing to its inadequate load-bearing capacity. In that case, pile foundation plays a significant role in transferring the load of a structure to a deeper, stronger soil layer. In Bangladesh, pile foundations are commonly used in most of the water control structures constructed by the Bangladesh Water Development Board. Here, in designing these structures, hydraulic design is given the highest priority over the foundation design. But foundation design, especially pile foundation, is a crucial element in design, and negligence of this important element can lead the structure to failure. Before constructing these structures, a pile load test is conducted following ASTM D1143-81 guidelines. According to BNBC (2020), for the pile load test, the applied load is 1.5 times the design load. But as a very conservative design load is used in these water control structures to account for the uncertainty, none of these pile load tests reach up to failure. There are many studies in Bangladesh comparing ultimate capacity from BNBC 2020, Meyerhof and others' empirical formulas with various interpretation methods of pile load test. But there is no study in Bangladesh to show the comparison between pile ultimate capacity from empirical formula and different pile load test extrapolation methods when the pile load test doesn't reach up to failure for water control structures, which are constructed by BWDB. This research intends to fill this gap by using different extrapolation methods like Chin's Method, Brinch Hansen's 90% Criterion, Mazurkiewicz's Method, Vander Veen's Method, and comparing their results with some widely accepted empirical formulas, such as NAVFAC DM 7.2, BNBC 2020, Meyerhof (1976). Birid (2017) applied these extrapolation methods to 23 static pile load test data. The study found that, while high test loads near ultimate capacity produced accurate estimates across all methods, low or partial loads generally led to overestimation, except in the case of the Davisson method. Arham et al. (2017) conducted six pile load tests on test piles with lengths in the range of 35m to 45m and with diameters of 1000mm in Pakistan, discovered that NAVFAC DM 7.02 gives 20% to 40% less pile capacity relative to the pile capacity evaluated from pile load test data. Previous studies demonstrating analyses of pile load test results of 22 projects across Bangladesh showed that Meyerhof (1976) gives the most accurate result for bored piles (Dey & Ansary, 2025). Since our pile load test result doesn't reach up to failure, based on these previously conducted studies, Meyerhof (1976) was adopted as a baseline for comparison with other methods.

2. METHODOLOGY

2.1 Pile Load Test

Pile load test was conducted following the test method recommended by ASTM D1143-81.

Figure 1: Pictures of pile load test (ASTM D-1143-07).

2.2 Work Flow Diagram

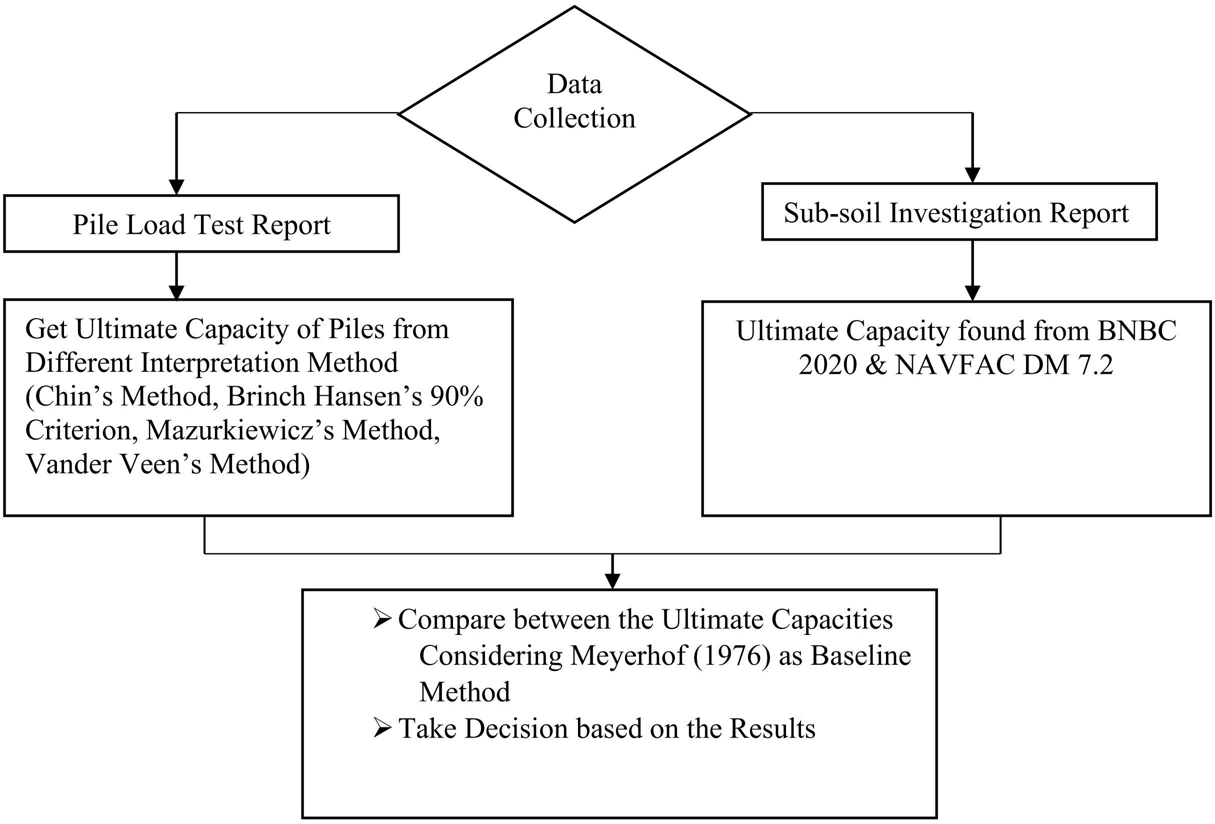


Figure 2: Methodology of the study.

2.3 Pile Capacity from Empirical Equations

Ultimate pile capacity is denoted as,

$Q_{ult}\,(KN) = Q_s + Q_b = f_s \times A_s + f_b \times A_b$ (1)

According to (Meyerhof, 1976),
equation for Cohesionless soil of driven pile,

Skin Friction, $fs = 2N_{60}\,(KPa) \leq 60\ kPa,$ (2)

End bearing for sand, $f_b = 400\ N_{60}\,(L/D)\ (in\ Kpa) \leq 400\ N_{60}$ (3)

For bored pile, *Skin friction = (Driven Pile Skin Friction)/3* (4)

End Bearing= (Driven Pile Skin Friction)/2 (5)

For Cohesive soil of bored pile, Skin Friction, $fs = \alpha * Cu\ (in\ KPa)$ (6)

End Bearing, $f_b = 9\ Cu\ (in\ KPa)$ (7)

According to (BNBC, 2020), for bored pile

Skin friction for sand: $f_s = 1.0\ N_{60}\ (in\ Kpa) \leq 60\ Kpa$ (8)

Skin friction for non-plastic silt: $fs = 0.9\ N_{60}\ (in\ kPa) \leq 60\ kPa$ (9)

End bearing for sand: $f_b = 15\ N_{60}\,(L/D)\ (in\ Kpa) \leq 1500\ N_{60}\ \&\ \leq 4000\ Kpa$ (10)

End bearing for non-plastic silt: $f_b = 10\ N_{60}\,(L/D)\ (in\ Kpa) \leq 100\ N_{60}\ \&\ \leq 4000\ Kpa$ *(11)*

Skin friction for cohesive soil, $f_s = 1.2\ N_{60}\ (in\ Kpa) \leq 70\ Kpa$ (12)

End bearing for cohesive soil, $f_b = 25\ N_{60}\ (in\ Kpa) \leq 4000\ Kpa$ (13)

2.4 Ultimate Capacity from NAVFAC DM 7.2 (GEO-5)

Pile base resistance for non-cohesive soils is given by (website of GEO-5),

$R_b = \sigma_{efb} \times N_q \times A_b$ (14)

Where, σ_{efb}=Effective Stress on Pile base,
N_q=Bearing Capacity Factor
A_b=Area of pile base

For cohesive Soil, Pile Base Resistance, $R_b = C_u \times N_c \times A_b$ (15)

N_c=Bearing Capacity Factor, C_u=Undrained Shear Strength

Pile shaft resistance for non-cohesive soils is given by:

$$R_s \text{ (in KN)} = \Sigma (K_j \times \sigma_{ef,j} \times \tan \delta_j \times A_{s,j}) \quad (16)$$

Where, K_j – coefficient of lateral earth pressure for layer j
$\sigma_{ef,j}$ – effective vertical stress at mid-depth of layer j
$\tan \delta_j$ – tangent of the interface friction angle between pile and soil in layer j
$A_{s,j}$ – surface area of pile shaft in layer j
For cohesive soils (clays),

$$Rs \text{ (in KN)} = \sum \alpha_j \times c_{u,j} \times A_{s,j} \quad (17)$$

Where,
α_j – adhesion factor for layer j
$c_{u,j}$ – undrained shear strength of soil in layer j

2.5 Ultimate Capacity from Pile Load Test

Chin's Method

This method assumes that load-settlement curve is a hyperbolic curve. It states that, when the settlements (**S**) are plotted against the settlement divided by corresponding load (S/Q), the crossing points of (**S**) and (S/Q) plot is a straight line having a slope ($C1$) and a Y-intercept ($C2$). The ultimate load is then equal to (1/ $C1$) (Yousif & Ali, 2021).

Brinch Hansen's 90% Criterion

Brinch-Hansen (1963) developed a method which assumed that, the failure is achieved from the assumption that hyperbolic relationships exist between the load and settlement. For this, a hyperbolic curve is fitted to our existing available data according to the below equation,

$$Q = S/(C_1 S + C_2) \quad (18)$$

Brinch's Hansen states that ultimate capacity is the load which gives twice the movement of the pile head as obtained for 90 percent of that load. Based on this assumption, ultimate capacity is calculated from the plotted graph (Yousif & Ali, 2021).

Vander Veen's Method (1953)

According to this method, Ln (1-Q / Qu) is plotted for different values of Q. When the plot becomes straight line, then the corresponding Qu represents the correct failure load (Mishra et al., 2019).

Mazurkiewicz's Method (1973)

Mazurkiewicz provides us with a hypothesis that the resulting drawing is a curve of load-settlement approaching parabolicity. These operations are carried out by selecting a set of settelment lines for the pile head separated at equal intervals and differentiated on the load axis by the respective loads. Then, at a 45-degree angle to the loads defined, a line is drawn. The ultimate load is the intersection of this line with the load axis (Adel & Shakir, 2022).

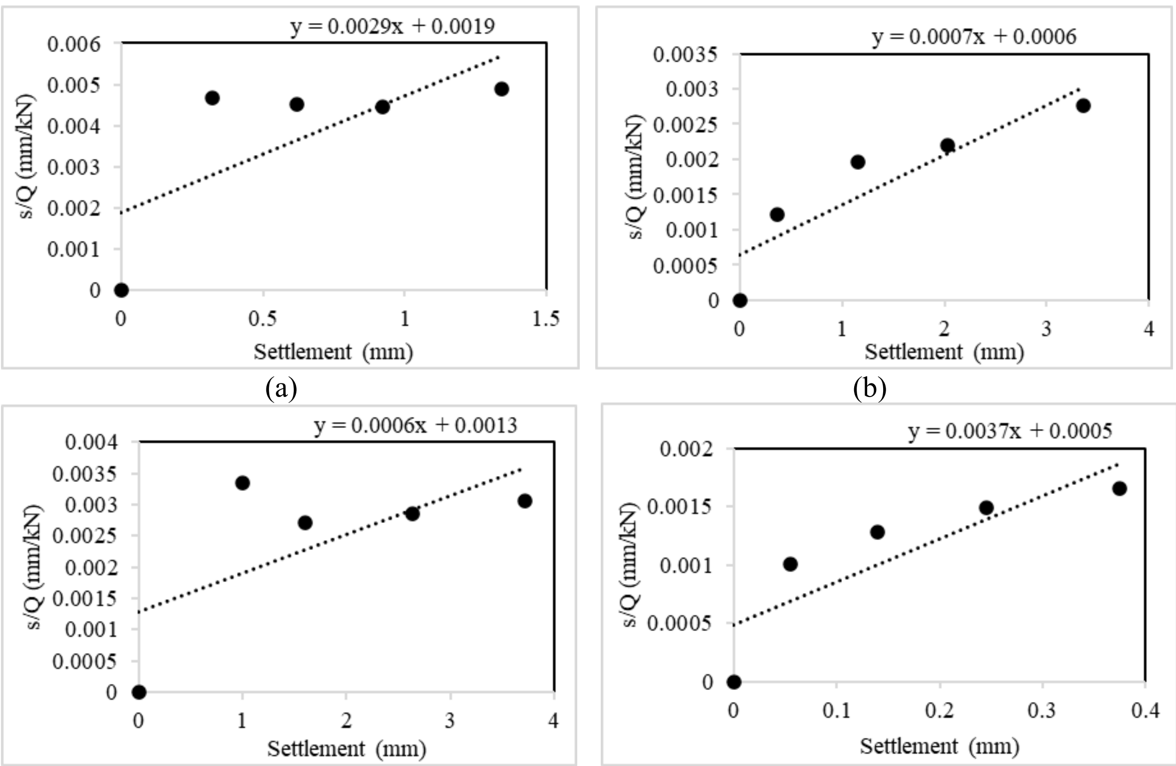
3. RESULT AND DISCUSSION

Sub-soil investigation report and 4 pile load test results were collected from three hydraulic structures that are Laldiar Char Sluice, Saherkhali Sluice and Domkhali Sluice. These sluices are located in South Patenga and Mirsharai upazila in Chattogram district. Here, three different pile lengths, which are 14.5m, 35m, 16m and three different diameters, which are 600mm, 800mm and 750mm are used.

Table 1: Description and location of all pile load test.

Sluice Name	Test Pile No	Location	Pile Length	Pile Dia
Laldiar Char SluiceTP-02	TP-02	South Patenga, Chattogram	14.5m	600mm
Saherkhali Sluice TP-01	TP-01	Mirsharai, Chattogram	35m	800mm
Saherkhali Sluice TP-02	TP-02	Mirsharai, Chattogram	35m	800mm
Domkhali Sluice TP-02	TP-02	Mirsharai, Chattogram	16m	750mm

Pile ultimate capacity is calculated from empirical methods BNBC, NAVFAC DM 7.2, Meyerhof's theory. The predicted capacity of 4 cast-in-situ piles from different extrapolation methods like Chin's Method, Brinch Hansen's 90% Criterion, Mazurkiewicz's Method, Vander Veen's Method of pile load test were computed and shown (Figure 3, Figure 4, Figure 5 & Figure 6). Here, for Chin's method, the settlements (**S**) are plotted against the settlement divided by the corresponding load (S/Q). The plot is a straight line. If the slope of this line is $C_{1,}$ then the ultimate load=1/ C_1 (Figure 3).



(c) (d)

Figure 3: Ultimate capacity of piles from Chin's Method (a) Laldiar Char Sluice TP-02, (b) Saherkhali Sluice TP-01, (c) Saherkhali Sluice TP-02, (d) Domkhali Sluice TP-02.

For Brinch Hansen Method, load vs settlement is plotted and a hyperbolic curve is fitted to our existing available data according to equation (18). Then, the ultimate capacity is calculated based on the assumption that it is the load that gives twice the movement of the pile head as obtained for 90 percent of that load (Figure 4).

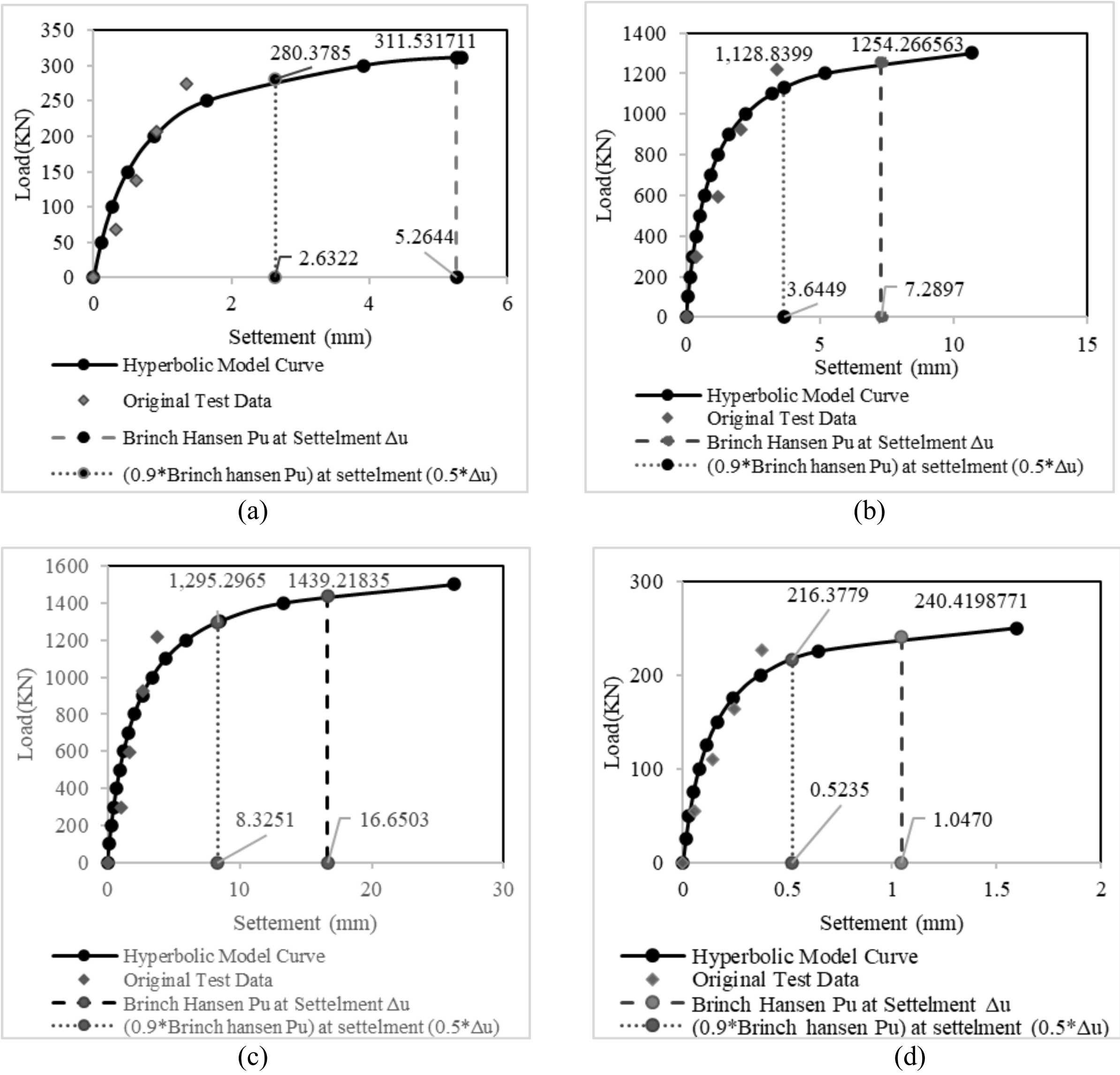


Figure 4: Ultimate capacity of piles from Brinch Hansen's 90% Criterion

(a) Laldiar Char Sluice TP-02, (b) Saherkhali Sluice TP-01, (c) Saherkhali Sluice TP-02, (d) Domkhali Sluice TP-02.

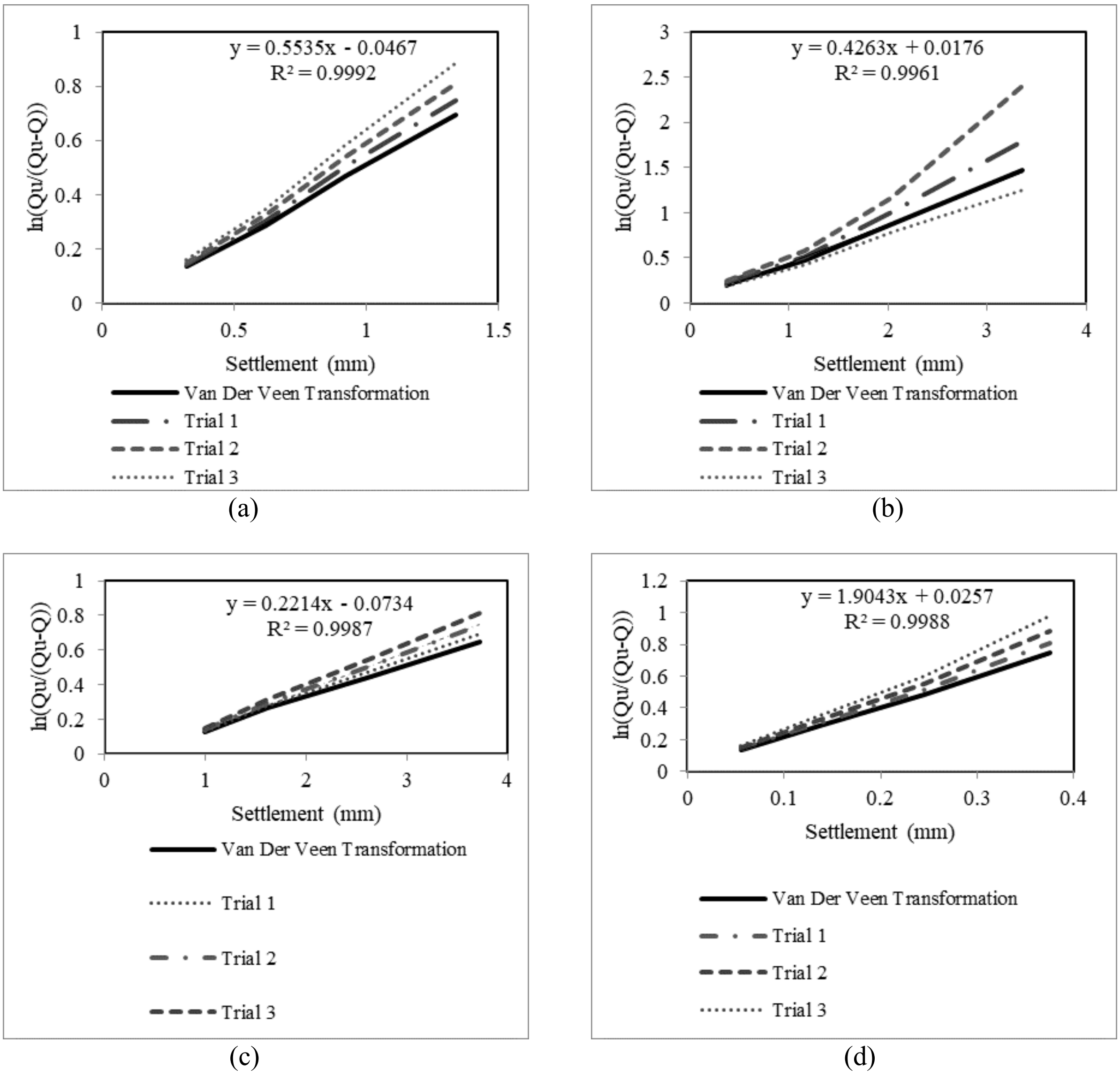


Figure 5: Ultimate capacity of piles from Vander Veen's Method (a) Laldiar Char Sluice TP-02, (b) Saherkhali Sluice TP-01, (c) Saherkhali Sluice TP-02, (d) Domkhali Sluice TP-02.

In Vander Veen's Method, Ln (1-Q / Qu) is plotted for different values of Q. Then the ultimate load is taken as the Q for which the plot becomes a straight line (Figure 5).

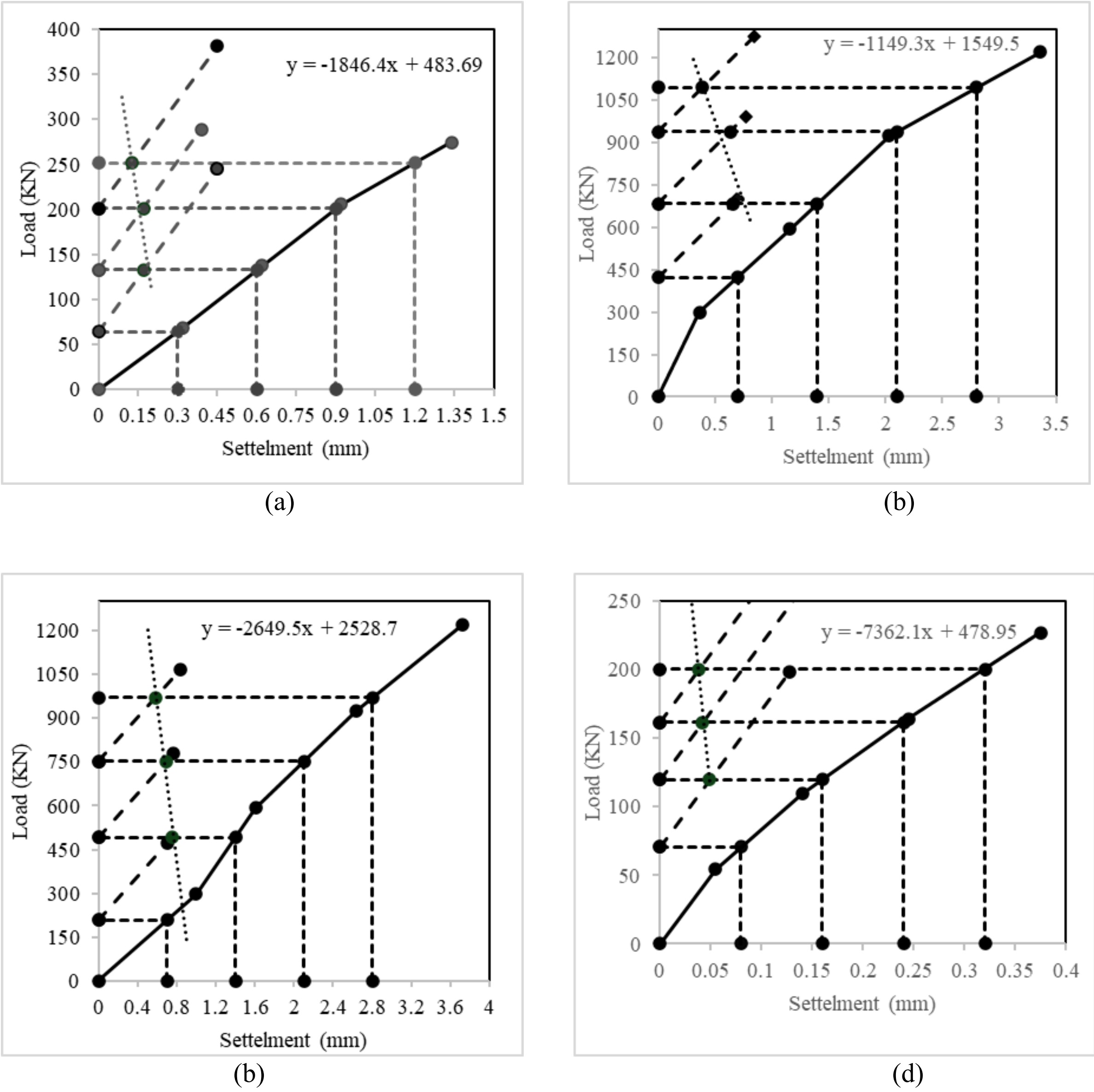


Figure 6: Ultimate capacity of piles from Mazurkiewicz's Method
(a) Laldiar Char Sluice TP-02, (b) Saherkhali Sluice TP-01, (c) Saherkhali Sluice TP-02,
(d) Domkhali Sluice TP-02.

For Mazurkiewicz's Method, the load vs settlement curve is drawn. A series of vertical and horizontal lines from the intersecting point of the plotted curve is drawn corresponding to the pile head equal movement. Then, from the intersection of the load axis, a 45° line is drawn which intersects with the next load line. The straight line passing through these intersection points ultimately intersects the load axis, which is the ultimate load (Figure 6).

Pile ultimate capacity from other empirical equations, like BNBC 2020, NAVFAC DM 7.2 is also calculated. Here, pile capacity from NAVFAC DM 7.2 is performed using GEO5 software. According to other conducted research (Dey & Ansary, 2025), Meyerhof (1976) gives the most accurate result for bored piles. As our pile load test result didn't reach up to failure, based on the previously conducted research, we fixed Meyerhof (1976) as the baseline and compared other methods with it (Figure 7). It showed that Vander Veen's Method gives the closest result to Meyerhof (1976). Mazurkiewicz's Method estimated a result almost close to Vander Veen's Method but gave a comparatively lower value than it. Then Chin's Method interpreted a lower value than Mazurkiewicz's Method, and the lowest value is provided by Brinch Hansen's 90% Criterion.

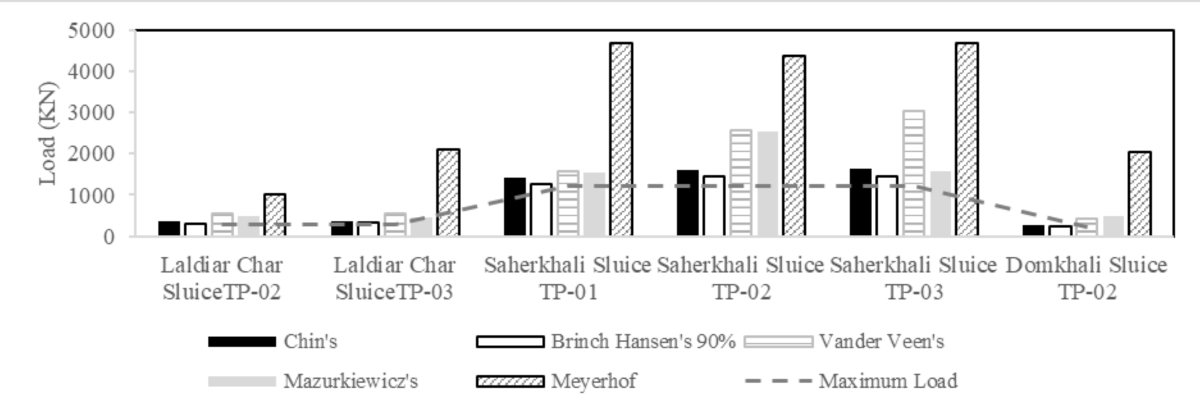


Figure 7: Comparison of ultimate capacity of piles.

Table 2: Statistical Analysis of Capacity Ratio ($Q_{predicted}/Q_{Meyerhof}$)

Method	Mean & Standard Deviation		(%) of Extrapolation
	Mean ,μ	S.D., σ	
BNBC 2020	0.598	0.231	
NAVFAV DM 7.2	0.741	0.166	
Chin's	0.277	0.101	26.46
Brinch Hansen's 90%	0.247	0.0895	12.41
Mazurkiewicz's	0.361	0.141	69.02
Vander Veen's	0.431	0.184	96.67

Statistical analysis based on capacity ratio ($Q_{predicted}/ Q_{Meyerhof}$) is determined to predict the accuracy of each method (Table 2). Statistical evaluation identified that Vander Veen's Method is ranked as the closest extrapolation method to the Meyerhof capacity, having mean capacity ratio μ=0.43, which indicates 57% underestimation. Mazurkiewicz's Method was the second closest method μ=0.36, but still underestimates ultimate capacity by 64%. Chin's Method & Brinch Hansen's 90% Criterion provided the least accuracy (μ=0.277 & μ=0.247), underestimating the capacity by nearly one-fourth.

Although Vander Veen's Method gives the highest mean accuracy, its high standard deviation (σ=0.184) compared to other methods indicates low precision. A similar case happened in Mazurkiewicz's Method (σ=0.141), which displays greater variability, indicating it is less reliable for consistent prediction. The reason behind this is due to the quantitative volatility of their non-linear curve-fitting functions. The high scatter of these two methods is the result of force-fitting a limited set of noisy data. On the contrary, although Chin's Method & Brinch Hansen's show the least accuracy, their lowest standard deviation (σ=0.101 & σ=0.089) indicates that their highly linear curve fitting approach boosts their reliability and makes them significantly less sensitive to noise and variation in the initial load points.

Among empirical methods, BNBC 2020 gives mean μ=0.598 & standard deviation (σ=0.231), which indicates it provides the closest value to Meyerhof (1976) by underestimating the maximum 40% capacity. It makes BNBC 2020 the most conservative of the two empirical methods presented. NAVFAC DM 7.2 shows mean μ=0.741 and standard deviation (σ=0.166), which gives the closest result to Meyerhof (1976) with high accuracy and precision between the two empirical methods. The high accuracy of these two methods makes them an ideal option for field calibration, and applying a simple calibration factor would significantly increase their accuracy.
The extrapolation percentage, which is evaluated relative to the maximum applied load, showed that Vander Veen's Method gives the maximum extrapolation percentage (91.67%). And the lowest extrapolation is found from Chin's Method & Brinch Hansen's Criterion.

Table 3: Structural Capacity of all the piles used in Sluices.

Sluice Name	Structural Capacity (KN)
Laldiar Char Sluice	4058
Saherkhali Sluice	7214
Domkhali Sluice	6341

The structural capacity of all the piles is very high, which is about 1.5 to 4 times higher than the geotechnical capacity derived from Meyerhof (1976). It indicates that pile will not fail structurally before taking the full geotechnically derived load.

4. CONCLUSIONS

The main objective of this study is to compare the pile ultimate capacity using different pile load test extrapolation methods and two empirical equation methods BNBC 2020 & NAVFAC DM 7.2, with Meyerhof (1976). Among all the interpretation methods, Vander Veen's Method shows the highest mean, standard deviation, and highest extrapolation percentage. It interprets the highest accuracy, and it can predict the highest percentage of the maximum applied load, but it has the lowest precision because its results are more scattered. This indicates Vander Veen's Method is best suited where very limited data are available, tolerating the higher scatter for the benefit of a better average prediction. On the other hand, Chin's Method has the lowest mean, standard deviation & percent extrapolation. It indicates that although it can extrapolate a small amount, it shows more consistent results. It makes it best suited for the pile load test, where more data is available, and less extrapolation is needed. Among all the empirical methods, BNBC 2020 gives the most conservative result with a reasonable amount of mean capacity ratio and standard deviation. It points out that BNBC 2020 can be an ideal choice for designers to remain on the conservative side. BNBC 2020 & NAVFAC DM 7.2 both method displays conservative values compared with the Meyerhof (1976). The high accuracy of these two methods indicates that applying a field calibration factor would help the designer predict the actual capacity of the pile. The high structural capacity of all the piles indicates that the pile is unlikely to undergo structural failure before taking the full geotechnically derived load. All these extrapolation methods can only be used in design when a reasonable amount of data is present, and a small percentage of extrapolation is needed. If less data is available, then it can only be used as a tool to predict ultimate capacity, not to use in design.

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DECLARATION OF USE OF AI

The authors declare that Artificial Intelligence (AI) tools were used only for language editing and grammar improvement to improve clarity and readability of the paper. The AI tools did not contribute to data collections, data analysis, research methodology, results, or scientific conclusions.

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