Optimization of End Bearing Capacity of Bored Piles on Rock Based on Field Measurements

B.A.C. Danushka[1*], N.H. Priyankara[1], A.M.N. Alagiyawanna[1] and K. Senevirathe[2]

[1]Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna, Hapugala, Galle, SRI LANKA.
[2]Department of Interdisciplinary studies, Faculty of Engineering, University of Ruhuna, Hapugala, Galle, SRI LANKA.

Abstract

Bored piles are one of the famous deep foundation techniques which are practiced all over the world. Most bored piles are socketed into the bedrock to gain higher bearing capacity. However, the estimation of end bearing capacity for rock socketed bored piles is questionable in the design of piles. Although there are some pile load tests available to estimate the end bearing capacity which is very costly, it is not practicable to adopt them for small-scale projects. There are a lot of theoretical methods that have already been developed to estimate the end-bearing capacity of bored piles on rock and there is no clear indication of the accuracy of those methods to apply into the Sri Lankan context. Therefore, designers use different methods based on their experiences which may result in overestimated designs. As such, in this research study, different theoretical methods were compared with the pile load test results in Sri Lanka and concluded that the most reliable method/s to estimate the end-bearing capacity of rock socketed bored piles in Sri Lankan context. The suggested method/s in this research study can be directly applied to estimate the end-bearing capacity of bored piles without conducting any field load tests.

Keywords— *Bored piles,End Bearing Capacity,Rock Socketed*

Introduction

Numerous Civil Engineering Projects, including the construction of highway viaducts and other large-scale structures, face challenges in maintaining stability when weak subsurface layers are present at shallow depths. Consequently, shallow foundations cannot be relied upon for ensuring structural integrity. To address this concern, deep foundations, particularly bored piles, are employed to effectively transfer the structural load to the underlying hard strata. A common approach involves embedding the bored piles into the bedrock, thereby enhancing their end-bearing resistance significantly. This strategy proves crucial in ensuring the long-term stability and durability of such Civil Engineering Projects.

Pile foundations, as deep foundations, offer compelling reasons for their adoption.One significant advantage is their suitability in situations where the water table is high, posing potential stability concerns for the structure. Additionally, the compressibility of soil at shallow depths renders it inadequate to bear the substantial load imposed by large structures. Consequently, pile foundations become indispensable for ensuring structural integrity in areas near riverbeds and coastal regions, where the water table remains elevated. In such scenarios, opting for piling construction proves to be prudent.

The fundamental principle behind a pile foundation is to efficiently transfer the load of the superstructure to a hard stratum or rock strata beneath the ground. Pile foundations can be classified based on their fundamental design function[1].In terms of the load transfer mechanism, piles are primarily divided into two categories: end bearing piles and friction piles. End bearing piles are designed to bear the load by directly resting on a solid, load-bearing layer or rock stratum at their base. On the other hand, friction piles derive their load-bearing capacity primarily from the frictional resistance developed along their sides as they interact with the surrounding soil.

In practice, there are instances where a combination of both end bearing and frictional mechanisms is employed, as illustrated in Figure 1. Such an approach is commonly used in the field to optimize the load-carrying capabilities of the pile foundation and enhance its overall performance based on specific site conditions and engineering requirements.

The 'End Bearing Capacity' (EBC) of a bored pile in socketed rock is dependent on many external and internal conditions and rock parameters. They may vary depending on the rock type, method of test, equipment, mechanism etc. Therefore, a lot of relationships have been developed to compute the EBC researchers.

Bored pile foundations are typically designed based on comprehensive data obtained from subsurface investigations conducted through boreholes. Soil and rock samples are extracted during these exploratory procedures, and subsequent laboratory tests are performed to assess their bearing characteristics. The design process aims to ensure that the pile

*Corresponding author: chamidudanushka123@gmail.com
Received: March 16, 2023, **Published:** October 06, 2023

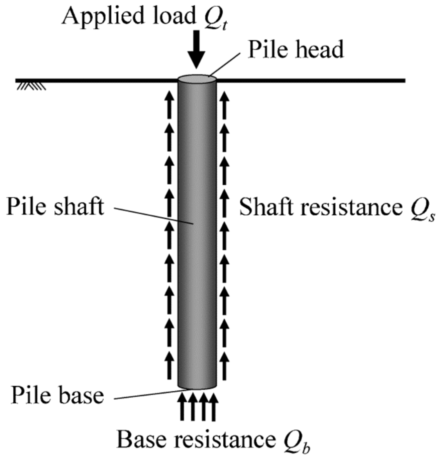

Figure 1: *Components of resistance of a pile*

foundation's load-bearing capacity aligns with the deduced parameters derived from the results of these exploratory boreholes and soil/rock tests. By incorporating this vital information, engineers can make informed decisions regarding the appropriate specifications and dimensions of the bored pile foundation to ensure its stability and effectiveness in supporting the intended structure[1]. The usual practice is to verify the load bearing capacity of the piles in the field, using a 'Static Load Test' (SLT) or 'Pile Dynamic Analysis' (PDA). It is difficult to conduct field pile load tests for small scale projects due to economic constraints. As such, it is a need of the hour to select the most reliable theoretical method/s to precisely estimate the EBC of the bored piles. Despite the multitude of theoretical methodologies developed by researchers to assess the bearing capacity of bored piles, investigations into the reliability of these approaches through field measurements remain scarce. The validation of these theoretical methods through direct comparison with field load test results, tailored to specific local geotechnical conditions, has been notably limited[2]. The applicability of these methods for the Sri Lankan context is questionable in pile designing and the reliability of the existing methods the for Sri Lankan context needs to be investigated.

Due to the unavailability of the most reliable methods to estimate end bearing capacity of bored piles in the Sri Lankan context, most designers adopt the guidelines of the Construction Industry Development Authority (CIDA) to estimate carrying capacity. However, it was reported that field measurements are much higher than design values, which are obtained using the CIDA method, leading to over-designing the bored piles. As such, some designers use thumb rules based on their experience to estimate the end bearing capacity of bored piles, which may lead to adopting a low factor of safety on bored pile design. As such, this research study aims to conclude the most reliable method/s to estimate the end-bearing capacity of rock socketed bored piles in Sri Lankan context by comparing the different theoretical methods of the pile load test results which were conducted in different areas in Sri Lanka. Indeed, the study is going to investigate whether the method of pile test has any influence on the obtained results.

Literature Review

A literature review yielded seventeen (17) theoretical methods for evaluating the end bearing capacity of bored piles. However, not all of these methods are applicable for evaluation due to various potential reasons leading to their expurgation (Table 1) according to the sample analysis for failure pile test and previous studies[2, 3].

Consequently, out of the initial pool of theoretical methods, only nine (09) were selected for determining the ultimate end bearing capacity (q_{max}) of the bored piles under consideration as follows (Table 2).

Where:

J is a correction factor depending on the nature of discontinuities, C is the cohesion of rock mass and N_{cr} is the modified bearing capacity factor, σ_c is Uniaxial Compressive Strength (UCS) of rock, ϕ is drained friction angle and F (which is taken as 5)is a recommended safety factor(Table 2)[2, 3]

(VI) CIDA guidelines

Table 1: *Reasons for expurgated methods*

Expurgated Method	Reasons for expurgation
Coates (1967)	Highly overestimated
CGS (1985)	Highly overestimated Highly depending on the assumptions (Fracture spacing & aperture)
IRM/ Rowes and Armitage (1987)	Highly over-estimated
ARGEMA (1992)	Highly over-estimated
AASTHO,a,(1996)	Highly over-estimated
Code for Design Building Foundation (1998), China	only applicable for piles terminated at weathered rock zone
AASTHO,b,(1996)	Minimum required RQD value is 65 (> 65%)
Zhang (2010)	Minimum required RQD value is 65 (> 65%)

Table 2: *Selected theoretical equations*

No	Theoretical Method	Equation
(I)	Kulhaway and Goodman (1987)	$q_{\max} = \frac{\sigma_c \cdot (N_{\emptyset}+1)}{F}$ $N_{\emptyset} = \tan^2\left(45 + \frac{\phi}{2}\right)$
(II)	Tomlinson (1993)	$q_{max} = 0.33\sigma_c$
(III)	Zhang and Einstein (1998)	$q_{max} = 4.83\sigma_c^{0.51}$
(IV)	Vipulanandan *et al.* (2007)	$q_{max} = 4.66\sigma_c^{0.56}$
(V)	Bishnoi (1968)	$q_{max} = J.C.N_{cr}$ $N_c r = 2\tan(45 + \phi/2)$

According to the guidelines published by the Construction Industry Development Authority (CIDA), the estimation of end bearing capacity on rock is advised through the utilization of a graphical method, as outlined in the second edition of ICTAD/DEV/15, published in 2011. This graphical method correlates the end bearing capacity with two key parameters: the Unconfined Compressive Strength (UCS) value and the 'Rock Quality Designation' (RQD) value[4]. The specific graphical representation depicting this relationship can be found in BS8004 1986 [5]. By employing this graphical approach, engineers and professionals in the construction industry can effectively estimate the end bearing capacity on rock, considering the crucial factors of UCS and RQD values, thereby facilitating reliable and informed foundation design decisions.

(VII) RMR Method

The determination of allowable end bearing capacity based on the Rock Mass Rating (RMR) system, initially proposed by Bieniawski[6], is presented in Table 3.

(VIII) Hong Kong Guidelines

The Hong Kong guidelines refer the Code of Practice for Foundations British Standards 8004[7] to estimate the end bearing capacity on rock. According to this code, the estimation of end bearing capacity on rock is categorized into four regions based on specific parameters such as the Unconfined Compressive Strength (UCS) value, Core Recovery (CR) value, and the nature of the rock material[7].

Table 3: *RMR Method*

Parameters	RMR value			
	<40	50	70	88
Allowable bearing capacity (kPa)	3000	5000	10000	14500

**Note: Recommended safety factor 3.0 and interpolation is allowed.*

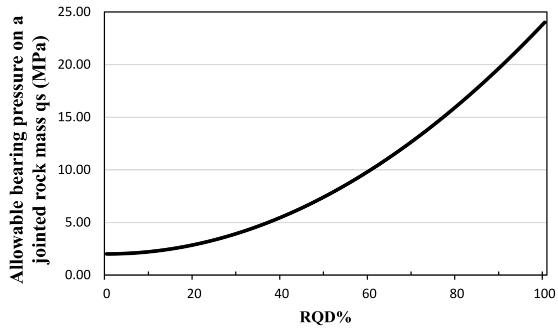

Figure 2: *Peck* et al. *Method*

(IX) Peck *et al.* Method[8, 9]

Peck *et al.* [8] suggested a semi-empirical correlation between allowable bearing pressure and 'Rock Quality Designation' (RQD) directly as shown in Figure 2. A safety factor of 3.0 was recommended in the method of Peck *et al.*

Methodology

The methodology of the study can be represented in a flow diagram as shown in Figure 3.

Collection of Pile Data

Initially, a total of 12 pile load tests were collected, comprising 7 SLT and 5 DLT. However, due to limitations in accessing the necessary data, some piles

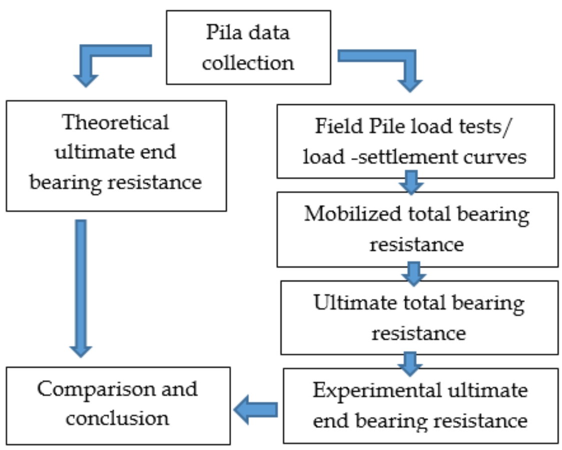

Figure 3: *Flow of Methodology*

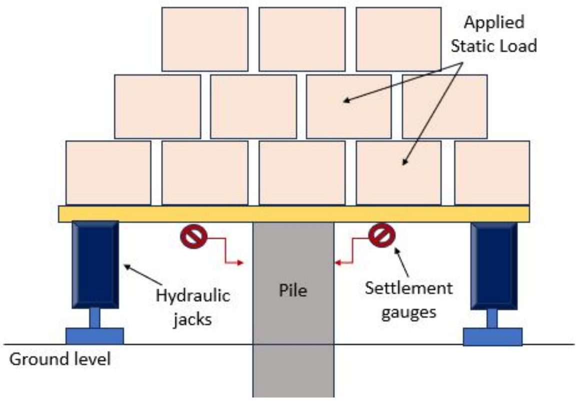

Figure 4: *Static Load Test (SLT)*

lacked the required information to evaluate their theoretical end bearing capacities accurately. Consequently, after careful consideration and screening, 7 pile tests were selected from various construction projects in Sri Lanka, as shown in Table 4.

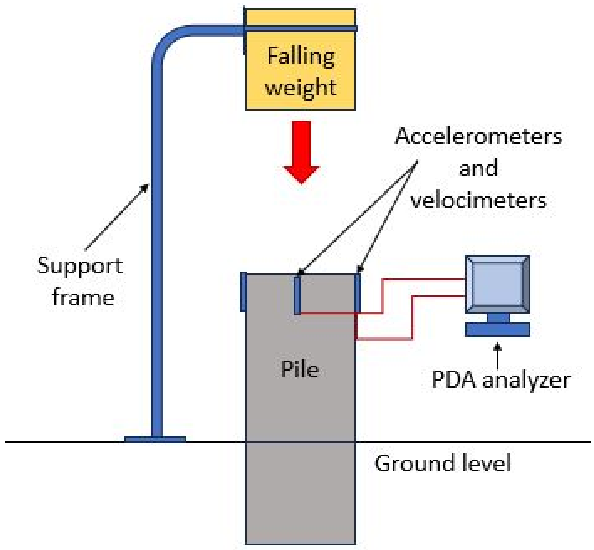

Figure 5: *Dynamic Load Test(DLT)*

Field Load Tests to Estimate the EBC

In general, piles undergo load testing at 1.5 times or 2.0 times the design load to assess their mobilized capacity without reaching the point of failure. This practice ensures that the tested piles can be safely included in the design, except for cases involving special failure load tests. To determine the mobilized bearing capacity of a bored pile, two common field methods are employed: SLT or Maintained Load Test (*MLT*), and DLT or PDA.

In the SLT, the pile top is supported using a steel structure, as depicted in Figure 4. Subsequently, substantial weights are placed on top of the structure, and the displacement of the pile top is measured over time. This process allows engineers to evaluate the pile's load-bearing behaviour under static conditions.

Table 4: *Details of selected piles*

Project Name / City	Test Pile No.	Type of load test
Port Access Elevated Highway (PAEH) project (Colombo)	TP-39	SLT
	TP-70A	SLT
	TP-70A	DLT
New Kelani Bridge Project (Kelaniya)	DEMA-BR1-7	DLT
Proposed housing project (Orugodawatta)	P-19	DLT
	P-76	DLT
	P-224	DLT

On the other hand, the Dynamic Load Test involves using specialized equipment to apply dynamic loads to the pile. The equipment records the pile's response to these dynamic loads, enabling the assessment of its dynamic properties and load-bearing capacity (Figure 5).

In both SLT and DLT, the measured 'Mobilized Bearing Capacity' (*MBC*) of the bored piles provides valuable information about their load-bearing behaviour under specific conditions. However, it is important to note that the MBC does not represent the ultimate bearing capacity of the bored piles. To compare the measured MBC with the ultimate end bearing capacity predicted by theoretical methods, an interpretation is required to estimate the ultimate capacity from the mobilized capacity. This conversion from mobilized capacity to ultimate capacity is typically performed using well-established graphical methods. Out of seven graphical methods (Davisson method (1973), Double tangent method, Brinch Hansen 80% method (1963), Chin-Konder method (1971), Fuller and Hoy method (1977), Hirany and Kulhaway Method (1989), Slope -tangent method[10, 11], only three most reliable graphical methods were selected based on a failure load test (According to the CIDA guideline: either the settlement for design load exceeds 6mm or settlement for 1.5 times design load exceeds 12 mm, pile is said to be almost failed) results which were conducted in New Maternity hospital project, Karapitiya, Galle, Sri Lanka as shown in Figure 6.

Based on the failure pile load test curve shown in Figure 6, it is evident that the actual ultimate failure occurred within the load range of $450 - 600$ *tons*

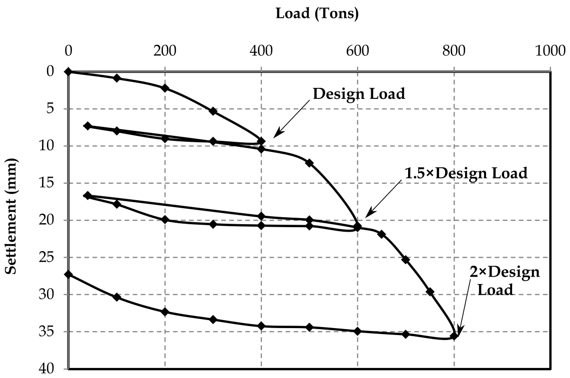

Figure 6: *Failure Load -Settlement Curve*

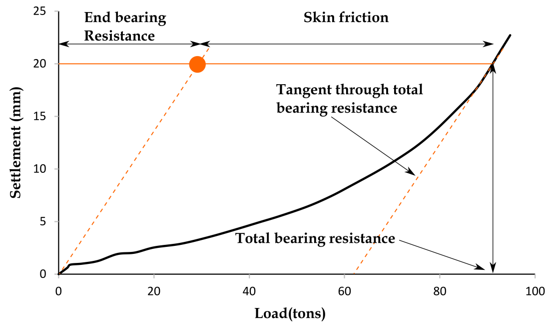

Figure 7: *Van Weele method*

(4490 – 5980 kN) according to the CIDA guidelines. However, the graphical methods employed to predict the ultimate total bearing resistance resulted in a deviation from the observed actual ultimate total bearing resistance in the failure test (Table 5).

According to the analysis (Table 6), the Double-Tangent method, Brinch Hansen 80% method and Fuller and Hoy (1977) methods were selected as the most reliable graphical methods to interpret the ultimate total bearing resistance. To determine the ultimate end bearing resistance from the ultimate total bearing resistance, it is necessary to separate the contribution of skin friction. Two graphical methods available in the literature for this purpose are the Van Weele method (1957) and Chin Method (1978)[12, 11].

Van Weele method (1957) Van Weele proposal entails a sophisticated observation regarding the behaviour of loaded piles. Initially, as a pile is subjected to loading, the predominant load-bearing mechanism is the skin friction along the shaft. This condition persists until the shaft slip attains a critical level, effectively activating the ultimate skin friction capacity of the pile. This behaviour is visually evident through the initial straight-line segment observed in the load-settlement curve. As the applied load continues to escalate, the ultimate skin friction reaches its full mobilization potential. Consequently, the load is then borne by the collective contribution of both the mobilized end bearing capacity and the fully mobilized ultimate skin friction.The point of intersection between the initial straight-line segment and the mobilized ultimate skin friction curve on the load-settlement curve signifies the ultimate end bearing resistance of the pile (Figure 7).

Chin Method (1978) The Graph of the ratio between the settlement and the load (S/P) and the settlement consists of two linear segments According to Chin (1978), the inverse of the slope of the second segment yields the total ultimate carrying capacity while the inverse of the slope of the first segment gives the ultimate skin friction capacity[10].

Based on the determined EBR results for both methods of pile load test results (Table 7) and some literature, the selection of the Van Weele method as

Table 5: *Selection of Skin Friction Method*

Pile No.	Type of Pile	Ultimate End Bearing Resistance (kN)					
		Van Weele method			Chin method		
		Double-tangent	Brinch Hansen	Fuller and Hoy	Double-tangent	Brinch Hansen	Fuller and Hoy
TP-39	SLT	12500	13495	-	8460	9455	-
TP70A	SLT	18000	24963	-	8860	15823	-
DEMA-BR1-7	DLT	2900	1330	3100	-	-	-
P-19	DLT	4500	12810	11000	-	-	-
P-76	DLT	2400	5330	3700	-	-	-
P-224	DLT	13100	19500	21000	-	-	-
TP70A	DLT	14000	20497	-	-	-	-

Table 6: *Comparison of Interpreted and actual ultimate bearing resistance*

Method	Predicted ultimate bearing resistance (kN)	Actual ultimate bearing resistance (kN)
Davisson Method (1973)	3390	4490-5980
Double-Tangent Method	4185	
Brinch Hansen 80% Method (1963)	5012	
Chin-Konder Method (1971)	12910	
Fuller and Hoy Method (1977)	2790	
Hirany and Kulhaway Method (1989)	Not satisfied (graphical matter)	
Slope-Tangent Method	2790	

the most reliable approach for separating the skin friction, because in most of the piles chin method estimates the considerable negative skin friction which was unacceptable.

After successfully separating the ultimate skin friction using the reliable Van Weele method, the subsequent step involved calculating the ultimate end bearing capacity for each of the selected pile load tests. This calculation was performed by combining the mobilized ultimate skin friction with the ultimate end bearing resistance. Because end bearing resistance is equal to the reduction of skin friction from the total resistance.

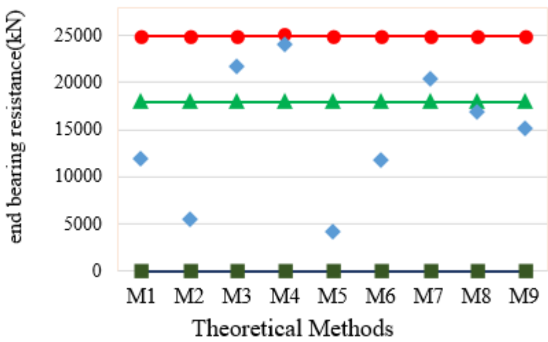

Figure 8: *Comparison 01 of EBR for TP-70A(SLT)*

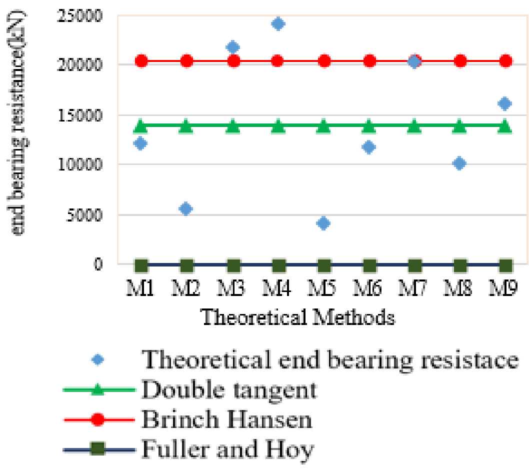

Figure 9: *Comparison 01 of EBR for TP-70A(DLT)*

Results and Discussion

By following the methodology theoretical and experimental ultimate end bearing resistance were calculated as shown in Table 7.

Total results were compared based on the method of testing under three categories. Because generated settlement curves through SLT and DLT Tests are different, it will highly be affected the graphical results. The comparison between theoretical (represented by scattered diamond symbols) and experimental (indicated by three connected straight symbols) end bearing resistance is plotted for one selected pile as a sample (comparison 1 in Table 8, Figure 8 and Figure 9). The analysis includes nine theoretical methods labelled M1 to M9.

Where: M1- Kulhaway and Goodman (1987), M2-Tomlinson (1993),M3- Zhang and Einstein (1998), M4-Vipulanandan et al. (2007), M5-Bishnoi (1968), M6- CIDA Guidelines, M7- RMR Method, M8- Hong Kong Guidelines, M9- Peck *et al.* (1974)

Conclusions

Since most of the parts of the methodology correlate with the graphical interpretation and the results, the sensitivity of the graphical data is a crucial matter in this study. Referring to comparison 1, illustrates that SLT piles yield higher EBR than DLT based on their settlement curves with less deviation from the predicted theoretical values. Because SLT, measures the actual settlement for loading while DLT predicts the load settlement behaviour based on software. It implies that the prediction is dependent on the method of pile test directly. Although SLT and DLT piles have shown a scattered pattern of matching with the theoretical values, the methods of M3- Zhang

Table 7: *Theoretical and Experimental End bearing resistance*

Pile No	End Bearing Resistance (kN)											
	Theoretical									Experimental (SFS-Van Weele)		
	Kulhaw ay and Goodman	Tomlin-son	Zhang and Einstein	Vipilan andan *et al.*	Bishnoi	CIDA guidelines	RMR	Hong Kong guidelines	Peck *et al.*	Double tangent	Brinch Hansen 80%	Fuller and Hoy
TP-39 (SLT)	14500	6718	23855	26594	5089	33929	33930	2544	57680	12500	13495	-
TP-70A (SLT)	12082	5598	21737	24013	4241	11875	20358	1696	15262	18000	24963	-
DEMA-BRI-7 (DLT)	10516	4873	16938	18924	4430	9425	7069	1178	15315	2900	1330	2100
P-19 (DLT)	10343	4792	20080	22011	3630	10857	10179	1017	10179	4500	12810	11000
P-76 (DLT)	19920	9230	28051	31772	6992	16965	13572	1696	16965	2400	5330	3700
P-224 (DLT)	17072	7910	19559	22625	7990	13360	13360	9543	9924	13100	19500	21000
TP-70A (DLT)	12080	5598	21737	24013	4241	11875	20358	1017	16289	14000	20497	-

and Einstein (1998) and M7- RMR method have performed on a reliable way with a theoretical prediction by making less deviation (comparison 3 in Table 8). Therefore, according to the gathered data Zhang and Einstein (1998) and the RMR method can be concluded as the most reliable methods to estimate the end bearing capacity for rock socketed bored piles in Sri Lankan context.

As a future direction of the study, efforts can be made to gather additional failure load test results from various sources, such as ongoing or completed geotechnical projects. The inclusion of more failure load test data will further strengthen the study's conclusions and validate the reliability of the recommended methods for estimating the ultimate end bearing capacity of bored piles for local conditions.

Conflicts of interest

The authors declare that there are no financial interests or non-financial conflicts or conflicts of interest related to this research that could have influenced this research.

Acknowledgments

We are particularly grateful and acknowledge for the expertise and resources provided by Geotech (Pvt). Ltd., Piletest consultant (Pvt). Ltd. and Soil and Mineral Engineering (Pvt)Ltd in Sri Lanka. Their contribution for providing sufficient pile load test results including the failure pile load tests and the relevant geotechnical investigation data for the research, significantly enhanced the scope and the quality of our

Table 8: *Comparison results*

Comparison	Piles	Objective	Most reliable method/s
1	TP-70A (SLT) and TP-70A (DLT)	Identify the influence on the testing method (for the same pile)	SLT EBR results are higher than DLT results and have less deviation from the theoretical predictions.
2	All SLT	Identify the most reliable methods separately	M1, M3, M4, M7, M8
	All DLT		M2, M3, M5, M7, M9
3	All the piles (at once)	Overall Result	M3 and M7

research. Without their unconditional support this research would not have been possible.

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