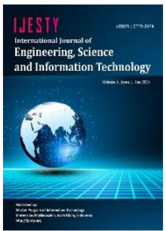
International Journal of Engineering, Science and InformationTechnology
Volume 5, No. 1 (2025) pp. 85-92
ISSN 2775-2674 (online)
Website: http://ijesty.org/index.php/ijesty
DOI: https://doi.org/10.52088/ijesty.v5i1.659
Research Paper, Short Communication, Review, Technical Paper



Comparison of Bored Pile Capacity Based on Analytical Design and Pile Load Test – A Case Study

Karina Meilawati Eka Putri*, Aulia Dewi Fatikasari, Hendrata Wibisana

[1]*Department of Civil Engineering, Faculty of Engineering and Science, Universitas Pembangunan Nasional Veteran Jawa Timur, Indonesia*

**Corresponding author Email: karina.meilawati.ft@upnjatim.ac.id*

The manuscript was received on 20 June 2024, revised on 25 August 2024, and accepted on 29 November 2024, date of publication 5 January 2025

Abstract

This paper presents a comparative study of bored pile ultimate capacity based on analytical design and field tests. The object of this analysis is the bored pile foundation of the Sei Alalak Bridge in Banjarmasin, Indonesia. The analytical design of pile ultimate capacity was carried out using the empirical methods provided by Reese and O'Neill (1988) and Meyerhof (1976). The calculation of pile ultimate capacity using the empirical method is based on SPT data from four boreholes representing soil data in the abutment, tower, and counterweight zones. Two pile load tests were used to validate the analytical design: pile driving analysis (PDA) and the bi-axial load test Osterberg Cell (O-Cell). The pile ultimate capacity from the empirical method is then compared to field tests regarding pile shaft resistance and end-bearing capacity. The analysis results indicate that the empirical methods tend to underestimate the pile's ultimate capacity by 30–60%. The results reveal that the Reese and O'neill (1988) empirical method generates a significantly lower pile ultimate capacity than Meyerhof (1976). This indicates that the Meyerhof (1976) method gives a closer result of pile ultimate capacity than the field test. On the contrary, the Reese and O'Neill (1988) method is more consistent with the PDA test results. As a result, in this study, the Reese and O'Neill (1988) method is preferred over the Meyerhof (1976) method for predicting the ultimate capacity of a bored pile since it has been demonstrated to be more reliable in estimating the pile's ultimate capacity.

Keywords: *Comparative Study, Empirical Method, Field Test, Pile Ultimate Capacity.*

1. Introduction

Piles and deep foundations are widely used to support the superstructure, particularly in large and sensitive constructions with significant loads applied. Pile foundations, precisely bored piles, are commonly used in urban building projects because they reduce soil disturbance, noise, and vibration [1], [2]. In practice, the analytical design of bored pile capacity is determined through empirical correlations utilizing field test results, such as the Standard Penetration Test (SPT) or Cone Penetration Test (CPT) results [3], [4].

In this study, the analytical design of the bored pile was carried out utilizing Reese and O'Neill's (1988) [5], [6] and Meyerhof (1976) [7], [8] empirical methods based on SPT test results. According to a study conducted by [9], the empirical method developed by Reese and O'Neill (1988) was reliable for estimating the ultimate capacity of a pile foundation using only soil data. The Meyerhof (1976) empirical methods have also shown a good correlation with field test results in a study conducted in the Shahid Rajaee Port project [8]. However, the correlation of soil parameters used throughout the design process results in numerous uncertainties and inaccuracies in the analytical design of bored piles. Thus, field tests, such as static and dynamic loading tests, are required to validate the analytical design [10].

Pile Driving Analysis (PDA) and Bi-axial Load Test Osterberg Cell (O-Cell) are used in this study to verify the bearing capacity of the piles. PDA is a dynamic load test that employs computerized software programs for data collection and interpretation. In the PDA test, the force and velocity signals are post-processed using CAPWAP software to obtain the total bearing capacity of a pile, as well as resistance distribution along the shaft and at the toe. CAPWAP simulates the pile and soil as segments and employs a linear spring-mass damping model to determine the shaft and tip resistance [11]. Based on the case presented by Fellenius [12], the CAPWAP-determined pile capacity matched very well with the capacity of the static loading test. Given that CAPWAP is relatively accurate at predicting pile capacity, further application of the CAPWAP method for pile capacity evaluation is justified. Moreover, PDA is a standard test for pile testing because it is more efficient, cost-effective, and environmentally friendly than the usual static loading test method, eliminating the need for heavy mobilization of dead weights on-site [13].

While the PDA test is dynamic, the O-cell test represents a static load test. The O-cell test is a hydraulically driven load test installed inside the pile that works in two directions: upward against shaft resistance and downward against the end bearing, effectively separating the shaft and end bearing resistance components [14], [15]. Furthermore, digital gauges are used to measure displacements, which are collected by an integrated computerized data-acquisition system [16]. The Osterberg-Cell test inexpensively provides high capacities, making it an effective alternative to test drilled shafts [15], [17].

The primary purpose of this paper is to compare the ultimate capacity of a bored pile based on PDA test results, O-Cell test results, and analytical design using Reese and O'Neill's (1988) and Meyerhof (1976) empirical methods in the Sei Alalak Bridge project, Banjarmasin, Indonesia. This case study will discuss the accuracy of each empirical method in predicting pile-bearing capacity.

2. Methods

2.1. Bored Pile Properties and Testing

The object of this study is the bored pile foundation located in Sei Alalak Bridge, Banjarmasin, Indonesia. Sei Alalak Bridge is a cable-stayed bridge that spans 850 meters long and 20 meters wide. This bridge was built to replace the Kayu Tangi Bridge, which is around 30 years old and serves as the primary access route between Banjarmasin and other South and Central Kalimantan places. The layout plan of the Sei Alalak Bridge is shown in Fig 1.

Fig 2 shows borehole layout for SPT field tests. The SPT tests consist of 4 boreholes drilled to 78–100 meters deep. Borehole BH-03 represents the abutment side of the bridge, boreholes BH-04 and BH-05 represent the pylon, and borehole BH-06 represents the counterweight side of the bridge.

The PDA test was carried out on 1 bored pile on each side of the abutment and counterweight. While the O-cell tests were performed on 3 bored piles in the pylon location, 1 bored pile was tested on the outer radius of the pylon and the other 2 on the inner radius of the pylon. All bored piles on the abutment, pylon, and counterweight sides of the bridge are designed to be 70 meters long and 1.8 meters in diameter.

Fig 1. Plan layout of Sei Alalak Bridge

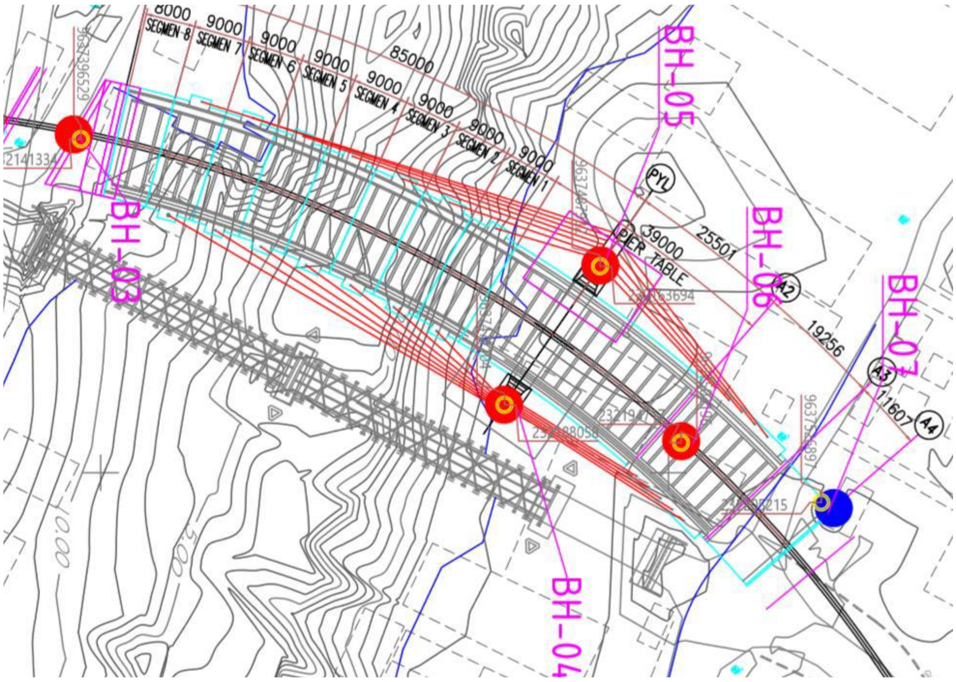


Fig 2. Layout of SPT test in Sei Alalak Bridge project

2.2. Subsurface Condition

The SPT test results obtained from each borehole indicate that the top layer of soil is soft clay throughout the first 25–35 meters. Under the clay layer lies an underlying sand layer about 10 meters thick. The remaining layer beneath the sand comprises hard to very stiff clay. Fig 3 shows the results of the SPT tests and the soil conditions for each borehole.

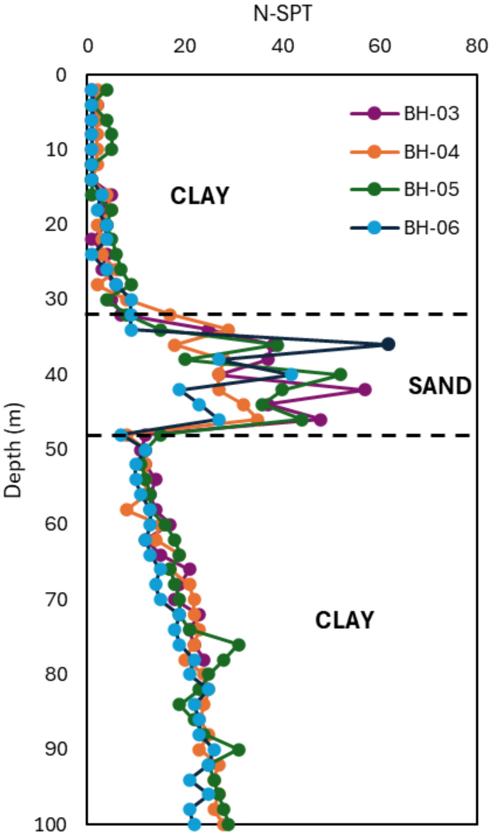


Fig 3. SPT results and soil conditions

2.3. Analytical Design of Bored Pile

The ultimate capacity of bored pile (Qu) consists of shaft friction capacity (Qs) and end bearing capacity (Qp). The ultimate capacity of the bored pile is expressed in the equation as follows [5]:

$$Q_u = Q_s + Q_p = A_s q_s + A_p q_p \qquad (1)$$

In the Equation 1, q_s, is unit skin friction capacity, and A_s is the pile shaft area, q_p is unit end bearing capacity, and A_p is cross section of the pile's toe.

Table 1 summarizes the pile-bearing capacity formulas for each empirical method utilized in this study. The unit skin friction and unit end bearing capacity equations were presented in detail based on the soil type. All calculations are based on empirical correlations with SPT data.

Table 1. Summary of bored pile capacity empirical method

The empirical method of pile capacity	q_s (unit skin friction capacity)	q_p (unit end bearing capacity)
Reese and O'Neill [3], [4]	For clay: $q_s = \alpha S_u$, $\alpha = 0.55$ for $S_u < 2$ tsf For sand: $q_s = \beta\sigma'_v \le 2$ tsf for $0.25 \le \beta \le 1.2$ Where $\beta = 1.5 - 0.135\sqrt{z}$ S_u = undrained shear strength of soil σ'_v = vertical effective stress z = depth of the pile embedded in the ground	For clay: $q_p = N_c S_u \le 40$ tsf which, $N_c = 6(1 + 0.2z/D_p)$ For sand: q_p (tsf) $= 0.6N$ for $N \le 75$ q_p (tsf) $= 45$ for $N > 75$ N = SPT blow count
Meyerhof [5], [6]	$q_s = nN_sA_sD$ n = pile shaft coefficient, 1 kPa N_s = average N-index along the pile shaft A_s = pile shaft area D = embedded pile length	$q_p = mN_tA_t$ m = pile tip coefficient, 120 kPa N_t = N-index at the toe of the pile A_t = the cross-section, the pile tip

3. Result and Discussion

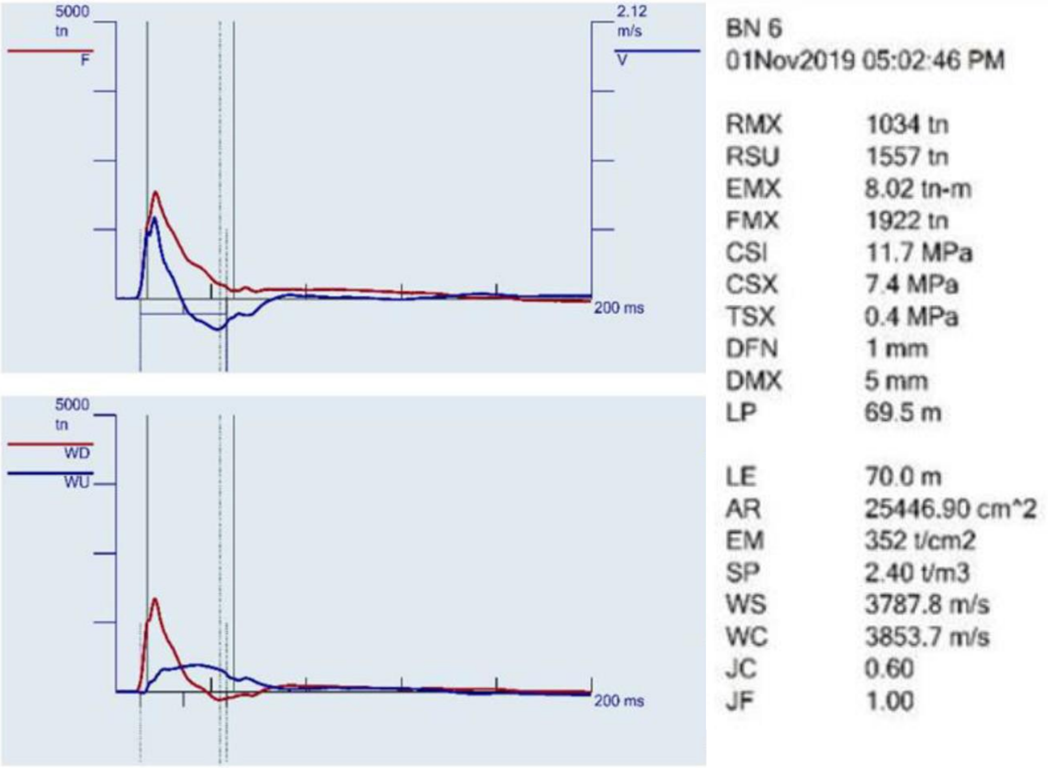
3.1. Pile Driving Analysis Test Result

Fig 4 shows the force-velocity and downward-upward wave of one of the piles evaluated with the PDA test. These PDA test results indicate that soil resistance on the piling shaft and toe combines static and transient or velocity-dependent dynamic resistance. Hence, the CAPWAP program is required to separate the static and dynamic soil resistances from the total soil resistance [18].

The pile ultimate capacity based on CAPWAP analysis is shown in table 2. Based on these results, it is clear that the pile-bearing capacity is dominated by its shaft friction resistance, which accounts for more than 75% of the pile's ultimate capacity. The ultimate bearing capacity of the pile is 9870 kN in the bridge abutment area and 15750 kN in the counterweight area. This is consistent with the SPT results, which show that the soil in the counterweight area has a higher NSPT value than in the abutment area

Table 2. Summary of PDA test results

Location	Qs (kN)	Qp (kN)	Qu (kN)
Abutment	7470	2400	9870
Counterweight	12740	3020	15750



BN 6
01Nov2019 05:02:46 PM

RMX	1034 tn
RSU	1557 tn
EMX	8.02 tn-m
FMX	1922 tn
CSI	11.7 MPa
CSX	7.4 MPa
TSX	0.4 MPa
DFN	1 mm
DMX	5 mm
LP	69.5 m
LE	70.0 m
AR	25446.90 cm^2
EM	352 t/cm2
SP	2.40 t/m3
WS	3787.8 m/s
WC	3853.7 m/s
JC	0.60
JF	1.00

Fig 4. Force-velocity wave on the pile results for PDA test located in bridge abutment

3.2. Osterberg Cell Test Result

Three of the 32 bored piles in the bridge pylon position underwent the O-cell tests. All the O-cell tests were performed according to ASTM D8169-18. The installation of the O-cell is shown in Fig 5.

The O-cell test on the outer side of the tower gives two different ultimate bearing capacity values since the tests were done on two different piles. The first test pile gives a result of 17580 kN, whereas the second provides the pile with an ultimate capacity of 15500 kN. For safety and conservative recommendations, the pile on the outer edge of the pylon area is assumed to have the lowest ultimate bearing capacity of the two tests, 15500 kN. The summary of the results is presented in Table 3. It showed that the pile's ultimate capacity is 17720 kN for the inner radius of the pylon and 15500 kN for the outer radius of the pylon.

Fig 5. Bi-axial Osterberg Cell installation

Table 3. Summary of O-Cell test results

Location	Qu (kN)
Outer Radius of Pylon	15500
Inner Radius of Pylon	17720

3.3. Analytical Design of Bored Pile

The analysis of pile bearing capacity is performed by utilizing Reese and O'Neill (1988) and Meyerhof (1976) empirical methods. Pile shaft resistance (Qs) and pile end bearing capacity (Qp) were calculated and shown in Table 4, respectively. Calculation is performed for each borehole to compare the pile bearing capacity from the empirical method and the field test.

Table 4. Summary of analytical design using Reese and O'Neill's (1988) empirical method

Location	Borehole	Analytical Design		
		Qs (kN)	Qp (kN)	Qu (kN)
Abutment	BH-03	8612.18	666.11	9278.29
Pylon	BH-04	8582.10	832.49	9414.59
	BH-05	9400.29	702.50	10102.80
Counterweight	BH-06	8027.11	570.26	8597.38

Table 5. Summary of analytical design using Meyerhof's (1976) empirical method

Location	Borehole	Analytical Design		
		Qs (kN)	Qp (kN)	Qu (kN)
Abutment	BH-03	5567.216	5496.531	11063.75
Pylon	BH-04	4866.01	6717.98	11583.99
	BH-05	5643.56	5801.89	11445.45
Counterweight	BH-06	4552.17	4580.44	9132.61

The results reveal that the Reese and O'neill (1988) empirical method generates a significantly lower pile ultimate capacity. According to the calculation method of Reese and O'Neill (1988), pile shaft resistance governs pile bearing capacity. Meyerhof (1976) is dominated by end bearing capacity, except for the pile at the abutment position. This is consistent with the formulas provided by each empirical method, with the Meyerhof (1976) end-bearing capacity formula significantly more significant than the Reese and O'Neill (1988) formula. At the same time, the Meyerhof (1976) formula comes with a frictional shaft capacity 2-3 times smaller than the Reese and O'Neill (1988) formula. Compared to the field data, Reese and O'Neill's (1988) empirical method agree with the PDA test result that the pile shaft capacity is the most significant component in the ultimate capacity.

3.4. Comparison of Analytical Design and Pile Load Test Result

The calculated bearing capacity utilizing the empirical method from SPT data versus the measured bearing capacity from the static and dynamic load tests is plotted in Fig 6 and Fig 7. Due to field test data limitations, results from the static O-Cell test and the dynamic PDA test are combined in the same graph. A diagonal line with a Qa/Qf = 1 ratio is drawn to demonstrate that the measured and estimated pile capacities agree to an exact degree, along with the data plotted for each borehole. It is helpful to compare the results of this study.

According to Fig 6, the Reese and O'Neill (1988) empirical method tends to underestimate the pile's ultimate capacity. This finding is supported by all data plots located below the Qfit line. This empirical method tends to underestimate the measured pile capacity by 57.8% in this study. The empirical method follows the same trend as the Reese and O'Neill method. Except for borehole BH-03, most data was found below the Qfit line. Although it exhibits the same trend, this method offers results closer to the Qfit line. The Meyerhof (1976) method underestimates the measured pile capacity by 37.19%. According to [19] research results, the Meyerhof (1976) method is typically pessimistic when estimating pile ultimate capacity.

These findings are consistent with the study conducted by [8], which shows that the method has the best-fit equation compared to Reese and O'Neill. The Meyerhof (1976) method is the best prediction method since it has a higher Qa/Qf in this study. However, there is a flaw in this method, as the PDA test findings contradict it. The PDA test results indicate that pile shaft capacity is more dominant than the end bearing capacity. The PDA results are more consistent with the Reese and O'Neill (1988) method, despite this method being more pessimistic than the Meyerhof (1976) method.

According to the graphs in Fig 6 and Fig 7, the results of this study are consistent with those of [10] and [20], which found that measured capacity by field test is often larger than predicted capacity using empirical methods. This gives designers confidence since their designs using the empirical method tend to be more conservative than the results of field tests, resulting in significantly safer constructions.

.

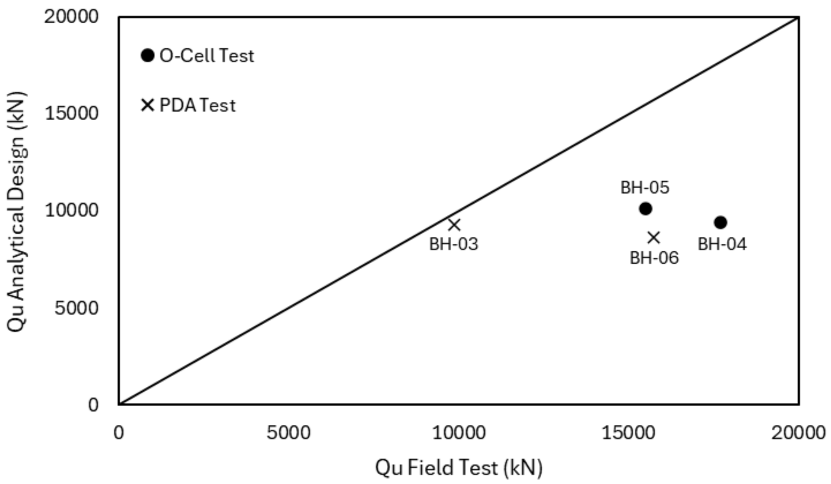


Fig 6. Field test results of ultimate pile capacity versus analytical design ultimate pile capacity for Reese and O'Neill (1988) method

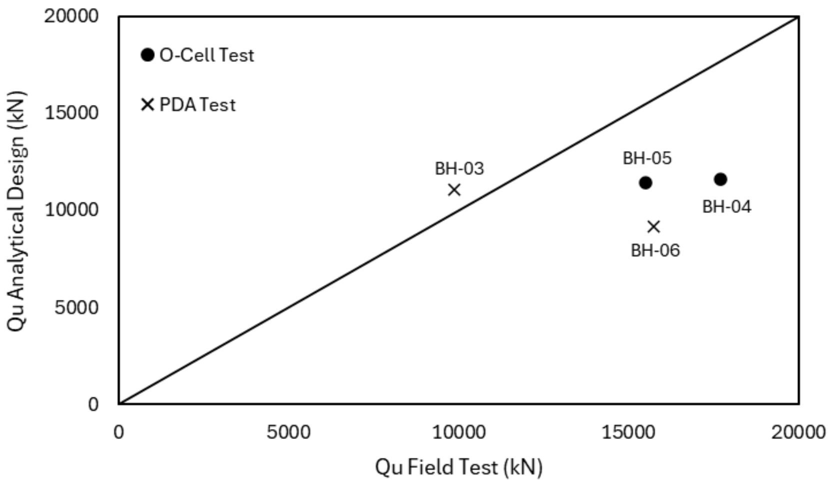


Fig 7. Field test results of ultimate pile capacity versus analytical design ultimate pile capacity for Meyerhof (1976) method

4. Conclusion

A comparison study of pile ultimate capacity based on analytical design employing empirical methods and field tests was presented in this paper. Field test results typically indicate higher pile capacity than empirical methods, giving planners confidence in their design. The Reese and O'Neill (1988) and Meyerhof (1976) methods are pessimistic regarding their estimates of the pile's ultimate capacity. All pile ultimate capacity estimations are 30–60% lower than the field result. Nevertheless, the Meyerhof (1976) method better fits the field test than the Reese and O'Neill (1988) method. Although Meyerhof's (1976) results are closer to the field test, they disagree with the PDA results, which show that pile shaft resistance is a more significant component than the end-bearing capacity of the pile ultimate capacity. Based on these findings, it can be concluded that while Reese and O'Neill (1988) are more conservative in estimating pile ultimate capacity, the estimates provided are more consistent with the PDA test results. Thus, the Reese and O'Neill (1988) method is preferred over the Meyerhof (1976) method for estimating the pile's ultimate capacity. This is also consistent with the conclusions of research [9] and [21], which suggested that the Reese and O'Neill (1988) method is a safe and reliable method for estimating pile ultimate capacity.

Acknowledgment

The author would like to thank Balai Pelaksanaan Jalan Nasional (BPJN) Kalimantan Selatan for their support and for providing information related to this study.

References

[1] S. Li, Q. Zhang, Q. Zhang, and L. Li, "Field and Theoretical Study of the Response of Super-Long Bored Pile Subjected to Compressive Load," Marine Georesources & Geotechnology, vol. 34, no. 1, pp. 71–78, Jan. 2016, doi: 10.1080/1064119X.2014.958883.
[2] M. G. Williamson, "Tunnelling Effects on Bored Piles in Clay," Apollo - University of Cambridge Repository, 2014.

[3] A. Oteuil et al., "Robust Analysis and Design of Bored Pile Considering Uncertain Parameters," Indian Geotechnical Journal, vol. 52, no. 3, pp. 720–734, Jun. 2022, doi: 10.1007/s40098-021-00588-7.

[4] M. M. Shoaib and M. Y. Abu-Farsakh, "Exploring Tree-Based Machine Learning Models to Estimate the Ultimate Pile Capacity From Cone Penetration Test Data," Transportation Research Record: Journal of the Transportation Research Board, vol. 2678, no. 1, pp. 136–149, Jan. 2024, doi: 10.1177/03611981231170128.

[5] R. M. Barker, J. M. Duncan, K. B. Rojiani, P. Ooi, C. K. Tan, and S.-G. Kim, "MANUALS FOR THE DESIGN OF BRIDGE FOUNDATIONS: SHALLOW FOUNDATIONS, DRIVEN PILES, RETAINING WALLS AND ABUTMENTS, DRILLED SHAFTS, ESTIMATING TOLERABLE MOVEMENTS, AND LOAD FACTOR DESIGN SPECIFICATIONS AND COMMENTARY," Washington, DC, Dec. 1991.

[6] H. S. Al-Jubair and J. M. Al-Battat, "Studying the Effects of Pile Load on Negative Skin Friction in Basrah Governorate," Research Journal of Applied Sciences, Engineering and Technology, vol. 18, no. 2, pp. 33–42, May 2021, doi: 10.19026/rjaset.18.6062.

[7] G. G. Meyerhof, "Bearing Capacity and Settlement of Pile Foundations," Journal of the Geotechnical Engineering Division, vol. 102, no. 3, pp. 197–228, Mar. 1976, doi: 10.1061/AJGEB6.0000243.

[8] H. Alielahi, D. Mousavi, and Z. addin Nadernia, "Statistical Assessment of Bearing Capacity of Cast-In-Situ Bored Piles Using Direct CPT and SPT Methods: A Case Study," Indian Geotechnical Journal, vol. 53, no. 3, pp. 698–714, Jun. 2023, doi: 10.1007/s40098-022-00690-4.

[9] Y. Lastiasih and I. D. Sidi, "Reliability of estimation pile load capacity methods," Journal of Engineering and Technological Sciences, vol. 46 B, no. 1, pp. 1–16, 2014, doi: 10.5614/j.eng.technol.sci.2014.46.1.1.

[10] B. H. Fellenius, "Basics of Foundation Design," Mar. 2023. [Online]. Available: www.Fellenius.net,

[11] R. Gohil and C. R. Parthasarathy, "Intelligent Assessment of Axial Capacity of Pipe Piles Using High Strain Dynamic Pile Load Tests in Offshore Environment," in Lecture Notes in Civil Engineering, Springer Science and Business Media Deutschland GmbH, 2023, pp. 271–287. doi: 10.1007/978-981-19-6513-5_24.

[12] B. H. Fellenius, "Analysis of results from routine static loading tests with emphasis on the bidirectional test," in Proceedings of the 17th Congress of the Brasiliero de Mecanica dos Solos e Egenharia, Comramseg, Goiania, Brazil, September, 2014, pp. 10–13.

[13] C. CHAN, W. CHONG, and R. A. Mukhtar, "Pile Dynamic Analyzer (PDA) Test: An overview of the pile integrity evaluation technique," Progress in Engineering Application and Technology, vol. 1, no. 1, pp. 48–54, 2020.

[14] J. O. Osterberg, "New device for load testing driven piles and drilled shafts separates friction and end bearing," in International conference on piling and deep foundations, 1989, pp. 421–427.

[15] Y. Barbosa, P. J. R. Albuquerque, and N. A. Chaves, "Experimental and Numerical Analyses of Two Instrumented Large Diameter Drilled Shafts Under Bidirectional Static Loading Test," International Journal of Civil Engineering, vol. 22, no. 2, pp. 241–257, Feb. 2024, doi: 10.1007/s40999-023-00880-y.

[16] M. Abualkhair, A. Hefny, and S. Elkhouly, "Assessment of empirical methods for interpreting bidirectional pile load test results," Ain Shams Engineering Journal, vol. 15, no. 7, p. 102791, Jul. 2024, doi: 10.1016/j.asej.2024.102791.

[17] J. H. Schmertmann and J. A. Hayes, "The Osterberg cell and bored pile testing-a symbiosis," in Proceedings: 3rd international geotechnical engineering conference, cairo university, cairo, egypt, 1997, pp. 3–12.

[18] T. A. L. Green and M. L. Kightley, "CAPWAP testing–theory and application," in Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, 2005, pp. 2115–2118.

[19] A. BOUAFIA, "Assessment of SPT-based methods of pile bearing capacity- Analysis of a database," in International workshop on Foundation Design & Soil Investigation in view of International Harmonization and Performance Based Design IWS Kamakura'02, Nov. 2002.

[20] K. M. Rollins, R. J. Clayton, R. C. Mikesell, and B. C. Blaise, "Drilled Shaft Side Friction in Gravelly Soils," Journal of Geotechnical and Geoenvironmental Engineering, vol. 131, no. 8, pp. 987–1003, Aug. 2005, doi: 10.1061/(ASCE)1090-0241(2005)131:8(987).

[21] G. Figueroa, A. Marinucci, and A. Lemnitzer, "Axial Load Capacity Predictions of Drilled Displacement Piles With SPT-and CPT-based Direct Methods," DFI Journal, vol. 16, no. 2, 2022, doi: 10.37308/DFIJnl.20220512.262.