Bearing Capacity and Settlement Analysis of Drilled Pile Foundation at The ASN-4 IKN Apartment Construction Project

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ABSTRACT

The relocation of the capital city requires the development of various essential infrastructures to support the functions of the National Capital. ASN-4 IKN Apartment is one of the vertical housing projects that implements land efficiency by constructing high-rise buildings. A thorough analysis of foundation bearing capacity and settlement is necessary, given the unique soil conditions and the lack of previous research in the area. If the foundation does not have sufficient bearing capacity, it may lead to settlement due to the loads applied above it. Therefore, both analyses are crucial during the planning process and should be monitored during implementation through load testing on drilled piles to obtain values for bearing capacity and settlement. This analysis aims to calculate and compare the bearing capacity and settlement of the foundation using analytical methods, the finite element method with the assistance of PLAXIS 2D software, and field load testing through the PDA Test. The ultimate bearing capacity results obtained from the Reese and Wright method are 1076,820 tons, with PLAXIS 2D software 805,576 tons, and from the PDA Test 727 tons. The percentage comparison of bearing capacity values between the Reese and Wright method and the finite element method against the PDA Test are 48,118% and 10,808%. Meanwhile, the settlement values using the empirical method are 10,082 mm, with PLAXIS 2D software 2,742 mm, and from the PDA Test 2,3 mm. The percentage comparison of settlement values between the empirical method and the finite element method against the PDA Test are 1,070% and 0,061%.

Keywords: bearing capacity, drilled pile foundation, PDA Test, settlement.

1. INTRODUCTION

The upper and lower structures form the two main structural components of high-rise buildings. The part of the building construction that is below ground level is the foundation, while the part of the building that is above ground level is the upper structure [1]. From the results of the soil investigation drill log conducted by PT. Brantas Abipraya at the ASN-4 Apartment, the soil characteristics at the depth of 2-3 meters are in the form of soft clay soil, then up to a depth of 40 meters the soil type is in the form of clay stone. The properties of this clay stone soil will be hard when dry and brittle when exposed to water. An in-depth analysis related to the bearing capacity and lowering of the foundation needs to be carried out, due to the unique soil conditions and the lack of research in the local area. If the foundation does not have enough bearing capacity, this will cause a settlement in the load on it [2]. Therefore, these two analyses are indispensable at the planning stage and monitored during implementation through loading testing on drilled piles to obtain bearing capacity and depreciation values [1].

According to the [3] bearing capacity of the foundation, it is assessed based on the calculation of the load bearing capacity of the pile point and the frictional resistance which can be determined by the Reese and Wright method based on the data of the results of the Standard Penetration Test (SPT) and laboratory tests. This calculation method can be used in two conditions, namely on cohesive soil and non-cohesive soil. Elastic settlement or direct settlement in the foundation occurs due to the application of weights that do not cause changes in moisture content. The magnitude of this settlement depends on the type of foundation and the material used [4]. The settlement of a single pile can be calculated using the Empirical method [5].

The use of software in the calculation of the bearing capacity and the settlement of the foundation also helps the analysis using the finite element method. PLAXIS 2D is one of the software that applies the element up method to analyze stability and deformation [6]. The process of quality control of foundations is usually carried out by direct testing in the field. One of these tests is called the Pile Driving Analyzer (PDA) Test. This test uses the Wave Analysis method, which is a testing technique that is carried out by hitting the pile repeatedly, through the PDA Test we can find out the dynamic effect of the drilled pile and ensure the quality of the foundation used as the bottom structure to support the load on it [7].

This research aims to analyze and compare the results of the calculation of bearing capacity and foundation reduction using analytical methods, element methods to the help of PLAXIS 2D software, and the results of loading tests in the field through PDA Test. Based on the results obtained, the PDA test value is used as a reference in the comparison of the two analytical calculation methods.

2. THEORY AND METHODS

2.1 Theory

2.1.1 Bearing Capacity

The bearing capacity of the drill mast is the maximum permissible vertical load. The largest load that a pile can support before it collapses is known as its capacity [8]

Using Equation 1, bearing capacity of the pile (Q_u) can be obtained by:

$$Q_u = Q_p + Q_s \tag{1}$$

With:

Q_u : Ultimate load bearing capacity (tons)
Q_p : End bearing capacity (tons)
Q_s : Frictional resistance capacity (tons)

The bearing capacity of the foundation is reviewed based on the soil data owned, namely the SPT (Standard Penetration Test), the implementation of the test refers to SNI 4153:2008. Standard Penetration Test (SPT) is one of the commonly used soil test methods to determine soil bearing capacity [9]. Each depth in drilling shows a different N-SPT value which is influenced by several factors, such as lithological type, rock strength, and other factors [10]. Reese and Wright (1977) is one of the methods of calculating the bearing capacity of a single mast based on SPT data [7].

a. End Bearing Capacity

$$Q_p = A_p \times q_p \tag{2}$$

With:

Ap : Cross-sectional area drilled pile (m^2)
q_p : End resistance per unit area ($tons/m^2$)
Q_p : End of Column Support (tons)

For cohesive soil:

$$q_p = 9 \times C_u \quad (3)$$

$$C_u = 6 \times N \quad (4)$$

With C_u : Soil cohesion (ton/m^2)

For non-cohesive soils:

Reese and Wright propose a correlation relationship between q_p and N-SPT as in Figure 1.

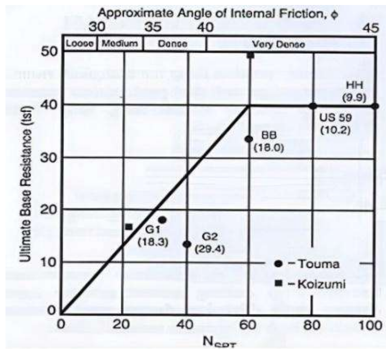


Figure 1. Ultimate bearing capacity of drilled pile on sandy soil

Where:

For N < 60 then q_p = 7 N (ton/m2) < 400 (ton/m2)

For N > 60 then q_p = 400 (ton/m2)

N is the average value of the tax return

b. Frictional Resistance Capacity

$$Q_s = f_s \times L \times P \quad (5)$$

With:

fs : Unit detainees skin friction (ton/m2)

L : Pile length (m)

P : Circumference of pile cross-section (m)

Q_s : Bearing capacity of the pile blanket (tons)

For cohesive soil:

$$f_s = \alpha \times C_u \quad (6)$$

With:

C_u: Soil cohesion (ton/m^2)

α : Adhesion factor (Reese and Wright (1977) $\alpha = 0{,}55$

For non-cohesive soils

For N < 53, then:

$$f_s = 0{,}32\ N\ (ton/m^2) \quad (7)$$

For 53 < N < 100 then f_s obtained through direct correlation with N-SPT related to shear resistance as in Figure 2.

2.1.2 Settlement

Elastic settlement or direct settlement in the foundation occurs due to the application of weights that do not cause changes in moisture content. The magnitude of this settlement depends on the type of foundation and the material used [4].

a. Empirical Settlement

The method used to analyze the subsidence on a single-pile foundation is the Empirical method (Vesic, 1970). This method estimates the settlement due to workload using certain

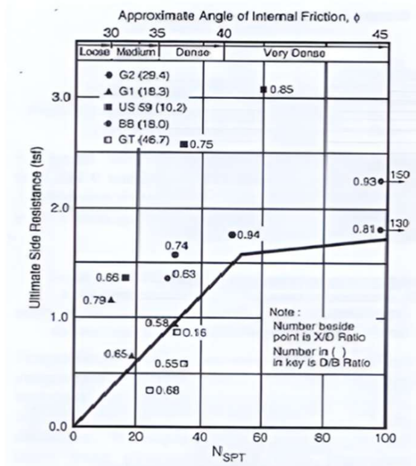


Figure 2. Ultimate skin resistance of drilled pile in non–cohesive soil

formulas or empirical relationships. The settlement relationship comes from factors such as the load received, the dimensions of the pile, the characteristics of the pile [11].

$$S_t = \frac{D}{100} + \frac{(Q \times L)}{(A_p \times E_p)} \quad (8)$$

With:

S_t : Single-pile foundation lowering (m)
D : Pile diameter (m)
Q : Applied load (tons)
L : Pile length (m)
A_p : Cross-sectional area of the pile (m^2)
E_p : Modulus of elasticity of pile material (ton/m^2)

b. Allowable Settlement

The permitted settlement of the pile foundation of a building is influenced by several factors, such as type, height, rigidity, function of the building, magnitude, speed and distribution of its settlement. The conditions for a safe reduction of the total settlement must be smaller than the reduction of the permit so that the foundation remains safe and does not cause structural damage [12].

$$S_{allow} = 10\% \times D \quad (9)$$

With:

S_{allow} : Allowable pile settlement (m)
D : Pile diameter (m)

2.1.3 PLAXIS 2D Software

The finite element method (FEM) is a computational technique for determining reasonably accurate solutions to integral and partial differential equations. PLAXIS 2D is being used for simulation of model which uses Finite Element Analysis (FEA) [13]. To simplify the analysis, the element approach is broken down into smaller components. Mathematical calculations, which are common in many branches of geotechnical engineering, provide the basis for this strategy [14]. The input value for the analysis procedure in PLAXIS 2D requires the current soil parameter value as well as the drill pile parameter value [15].

2.1.4 Pile Driver Analyzer Test

The recorded strain and velocity of the pile top are sent to a device called Pile Driving Analyzer (PDA) [16]. The PDA Test is a dynamic test to measure the ultimate axial pressure capacity of the pile, the final set, from the hammer impact carried out to obtain the integrity of the pile and the energy on the inner foundation. This test uses the Wave Analysis method, which is a testing technique that is carried out by hitting the pile repeatedly to get a wave response, through the PDA Test we can find out the dynamic effect of the drilled pile and ensure the quality of the foundation used as the bottom structure to support the load on it [7].

2.2 Methods

2.2.1 Research Programs

The research commenced with a comprehensive literature review to establish a theoretical foundation and identify relevant concepts and prior findings pertinent to the study topic. Secondary data utilized in this research were obtained from the service provider PT. Brantas Abipraya, comprising soil investigation results, laboratory test reports, drilled pile foundation specifications, and Pile Driver Analyzer (PDA) test data. Data processing involved correcting the Standard Penetration Test (SPT) N-values and correlating these adjusted values to derive soil parameters for input into the PLAXIS 2D finite element analysis software. The analysis was conducted based on the corrected SPT data and the specifications of the drilled pile foundations. Bearing capacity calculations for single piles were performed using both the Reese and Wright analytical method and the finite element method. Subsequent settlement analyses employed empirical approaches alongside finite element modeling through PLAXIS 2D. Additionally, comparative assessments were undertaken between manual calculations, software-assisted computations, and direct field testing results to evaluate consistency and accuracy.

2.2.2 Geotechnical Interpretation Data

Geotechnical interpretation data is data that contains related information index and engineering properties of the soil layer. In the collection of geotechnical interpretation data, soil investigation is carried out by the project and the data will be correlated by the author to obtain parameters that will be used in the calculation. This data consists of data drill-log, data from laboratory test results, correction of N – SPT values, correlation of N – SPT values to obtain soil parameters summarized in Table 1.

Table 1. Summary of soil parameter data

Parameter	Unit	Detail				
Common:						
Layer	-	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Depth	meter	0 – 2	2 – 12	12 – 17	17 – 20	20 – 30
Soil Type	-	Soft clay	Clay stone	Sandstone	Sandy clay stone	Clay stone
Condition	-	Undrained B	Undrained B	Drained	Undrained B	Undrained B
N	-	47	50	48	48	48
Soil Volume Weight:						
γ_{unsat}	kN/m^3	24	24	24	24	24
γ_{sat}	kN/m^3	24	24	24	24	24
Strong Parameters of Ground Shear:						
C_u	kN/m^2	288	300	0	288	288
φ	degree	0	0	30	0	0
Soil Stiffness Parameters:						

E`	kN/m^2	5000	50000	96000	25000	50000
v	-	0,1	0,1	0,2	0,1	0,1

2.2.3 PLAXIS 2D Modeling

Table 2. Pile parameter data summary

Item	Detail	Unit
Diameter	1000	mm
Concrete Quality	30	MPa
Specific gravity	24	kN/m^3
Modulus of Elasticity	25742960,2	kN//m^2
Axial skin resistance initial	487,261	kN/m
Axial skin resistance end	473,219	kN/m
Base resistance	2035,752	kN

PLAXIS 2D analysis is carried out by modeling drilled pile foundations according to real conditions in the field to accurately obtain soil characteristics and foundation behavior in planning and evaluating the bearing capacity and subsidence of the foundation [17]. The required soil parameters correspond to Table 1 and for the pile parameters in accordance with Table 2.

When the data to be input is available, the modeling steps carried out are as follows:

1) Specify Project Properties by setting the plane strain model.
2) Soil modeling with Input soil material data or soil parameter data. Then continued with geometric modeling of the soil layer according to Table 1.
3) Modeling of foundation structures with materials embedded beams 17 m long according to the parameters on Table 2.
4) Load provision by creating point load on the structure of 1000 kN for bearing capacity analysis and 98.1 kN for settlement analysis.
5) Divide the structure and soil model into smaller elements by generating mesh. For this analysis, a very fine mesh was used.
6) In the flow conditions level, the depth of the groundwater level is modeled by creating water level. The groundwater level in this research was modeled at a depth of 14.70 meters according to conditions in the field.
7) The calculation stage uses plastic analysis starting with the initial condition to analyze the initial effective voltage in the model. Then it is continued with the provision of a gradual load of 1000 kN until the structure fails for bearing capacity analysis. And the provision of a load of 98.1 kN for the settlement analysis.

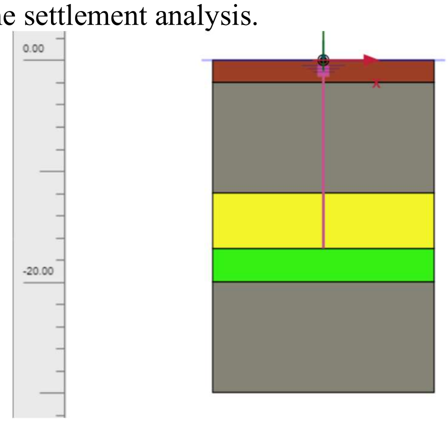


Figure 3. PLAXIS 2D modeling output

3. RESULTS AND DISCUSSION

3.1 Bearing Capacity of Drilled Pile Foundation Analysis

The calculation of the bearing capacity of the drilled pile foundation applies the value of N – SPT obtained from the construction project of ASN 4 IKN Apartment using the test point at Drillhole 1 (BH – 01). The dimensions of drilled pile are as follows:

- L = 17 m
- D = 1 m
- P = $\pi \times D = 3{,}14 \ \times 1 = 3{,}142\ m$
- Ap = $\frac{1}{4} \times \pi \times d^2 = \frac{1}{4} \times 3{,}14 \times 1^2 = \ 0{,}785\ m^2$

The following is the calculation of the ultimate bearing capacity based on data obtained through the calculation of N – SPT using the Reese & Wright method, from Equation 1 – 7.

a. End Bearing Capacity (Q_p)

$$C_u = 6 \times N$$
$$= 6 \times 48$$
$$= 288\ kN/m^2$$
$$q_p = 9 \times Cu$$
$$= 9 \times 288$$
$$= 2592\ kN/m^2$$
$$Q_p = A_p \times q_p$$
$$= 0{,}785 \ \times 2592$$
$$= 2035{,}752\ kN$$
$$= 207{,}589\ ton$$

c. Frictional Resistance Capacity (Q_s)

Layer 1 Soft Clay (0 – 2 meters) N_{60} = 47

$$C_u = 6 \times N$$
$$= 6 \times 47$$
$$= 282\ kN/m^2$$
$$f_s \ = \alpha \times Cu$$
$$= 0{,}55 \times 282$$
$$= 155{,}1\ kN/m^2$$
$$Q_s = f_s \times L_i \times P$$
$$= 155{,}1 \times 2 \times 3{,}142$$
$$= 974{,}522\ kN$$
$$= 99{,}374\ ton$$

Layer 1 Rock Clay (2 – 12 meters) N_{60} = 50

$$C_u = 6 \times N$$
$$= 6 \times 50$$
$$= 300\ kN/m^2$$

$$f_s = \alpha \times Cu$$
$$= 0{,}55 \times 300$$
$$= 164\ kN/m^2$$
$$Q_s = f_s \times L_i \times P$$
$$= 165 \times 10 \times 3{,}142$$
$$= 5183{,}63\ kN$$
$$= 528{,}583\ ton$$

Layer 3 Sandstone (12 – 17 meters) N_{60} = 48

$$f_s = 0{,}32 \times N$$
$$= 0{,}32 \times 48$$
$$= 15{,}36\ ton/m^2$$
$$Q_s = f_s \times L_i \times P$$
$$= 15{,}36 \times 5 \times 3{,}142$$
$$= 241{,}274\ ton$$

b. Ultimate Bearing Capacity (Q_u)

$$Q_u = Q_p + Q_s$$
$$= 207{,}589 + 869{,}231$$
$$= 1076{,}820\ ton$$

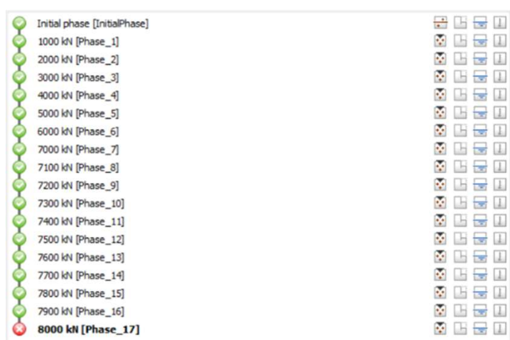


Figure 4. Load on PLAXIS 2D analysis

Based on the results of the analysis PLAXIS 2D, for modeling embedded beams Bearing capacity value obtained ultimate before the failure occurs. This analysis was carried out by providing a load in stages with an additional load of 1000 kN. Drilled pile have failed at 8000 kN loading due to soil collapse. To obtain more detailed results, reloading was performed after 7000 kN with load increments of 100 kN. The final result obtained by drilled pile has a bearing capacity ultimate of 7900 kN or equivalent to 805,576 tons seen in the Figure 4

3.2 Settlement of Drilled Pile Foundation Analysis

The calculation of the foundation settlement uses the Empirical method (Vesic, 1970) from Equation 8 and the element method up to the help of PLAXIS 2D software. The load used for the calculation of the settlement uses a load of 10 tons in accordance with the load in the PDA test. The results of the calculation of the settlement are as follows:

a. Settlement of the Empirical Method

$$S_t = \frac{D}{100} + \frac{(Q \times L)}{(A_p \times E_p)}$$

$$= \frac{1}{100} + \frac{(10 \times 17)}{(0{,}785 \times 2625051{,}389)}$$

$$= 0{,}01082\ m = 10{,}082\ mm$$

b. PLAXIS 2D Analysis

Figure 5 shows the magnitude of the settlement of the foundation drilled pile obtained through analysis using software PLAXIS 2D with weight equivalent load Hammer i.e. 10 tons. The settlement obtained is m or equivalent to 2,742 mm or $2{,}742\ \times 10^{-3}$ m.

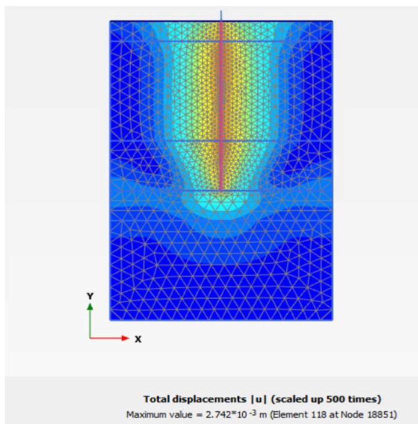


Figure 5. Total displacement of the foundation in PLAXIS 2D

c. Allowable Settlement

The condition for a safe comparison of the settlement is that the total settlement must be smaller than the settlement in the permit, with the settlement in permits in the Eq. 9.

$$S_{allow} = 10\% \times D$$

$$= 10\% \times 1$$
$$= 0{,}01\ m$$
$$= 100\ mm$$

3.3 PDA Test Results

The results of PDA testing on BP – 02 in Tower 8 ASN 4 IKN Apartment are shown in Table 3.

Table 3. Summary of PDA test results

No	Parameter	Description	Result
1.	DMX	Maximum settlement (mm)	4,6
2.	CFD	Permanent settlement (mm)	2,3
3.	EMX	Maximum energy transferred (MPa)	3,74
4.	CSX	Maximum compressive stress (ton m)	15,1
5.	BTA	Pile integrity value (%)	100
6.	RMX	Pile support capacity (tons)	727
7.	TSX	Maximum tensile tension (MPa)	4,5

3.4 Comparative Analysis of Bearing Capacity and Settlement of Drilled Pile Foundations

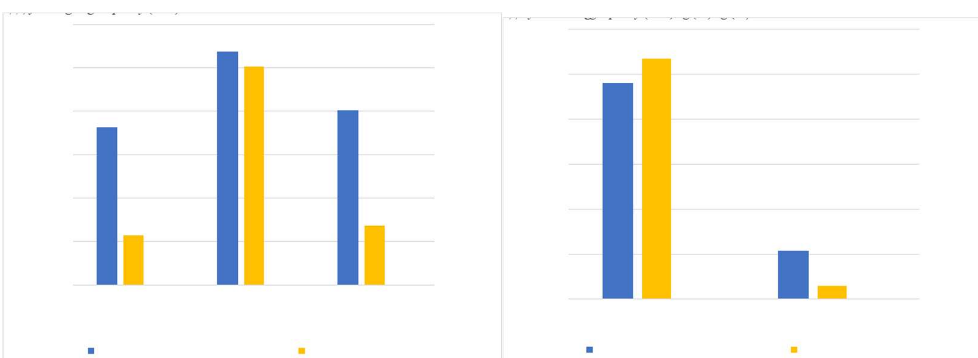
A recapitulation of the results of the calculations from the analytical method, the finite element method and PDA testing can be seen in Table 4 and Figure 6(a). Based on the results of the recapitulation PDA testing method, analytical method Reese and Wright, and the element method until it produces the result of bearing capacity ultimate of 727 tons, 1076,820 tons, and 805,576 tons. The analysis of the settlement of the PDA test method, the Empirical method and the element method resulted in a settlement of 2.3 mm, 10,082 mm, and 2,742 mm. Of these three methods, the smallest settlement value was obtained, starting from the PDA test, then the finite element method and the last one is the analytical method Reese and Wright. But the most important thing is that these three methods have met the value of the permit reduction, which is less than 100 mm. This indicates that the foundation design applied is adequate and safe to support the structural loads without posing a risk of damage due to excessive settlement.

Table 4. Recapitulation of bearing capacity and reduction of drilled pile foundations

Method	Ultimate Bearing capacity (tons)	Pile Settlement (mm)
PDA testing	727,000	2,3
Analytical Methods	1076,820	10,082
Finite Element Method with PLAXIS 2D	805,576	2,742

Table 5. Percentage of bearing capacity comparison and drilled pile foundation degradation to PDA test results

Method	Ultimate Bearing capacity for PDA Testing (%)	Pile Settlement against PDA Testing (%)
Analytical Methods	48,118%	1,070%
Finite Element Method with PLAXIS 2D	10,808%	0,061%



(a) (b)

Figure 6. (a) Recapitulation of the value of bearing capacity and the settlement in foundation; (b) Percentage graph of the comparison of bearing capacity values and degradation to the results of PDA testing

Table 5 and Figure 6 (b) shows the percentage of the comparison of bearing capacity values and settlements to the test results The difference in results in the three methods can occur due to some parameter assumptions that are entered into the calculation. In analytical calculations, the greatest results are obtained because when calculating, correlations are also used with the assumption of certain soil conditions, besides that this method tends to provide higher values because of its planning nature and conservative in some assumptions. For PDA testing, it produces different values but tends to be more significant because the response measurement is carried out during the piling process in accordance with the conditions in the field so that it is more representative of the actual conditions. The calculation method that comes closest to the results of PDA testing is the element method with the help of software PLAXIS 2D. This is due to the use of the parameters in the PLAXIS 2D more than analytical calculations. Thus, modeling result is better to represent the soil conditions in the field.

4. CONCLUSIONS

a. The results of the drilled pile foundation bearing capacity analysis using the Reese and Wright method and the element method resulted in the ultimate bearing capacity values of 1076,820 tons and 805,576 tons.
b. The results of the analysis of the settlement of the drilled pile foundation by the Empirical method and the element method obtained a settlement of 10,082 mm and 2,742 mm.
c. In the bearing capacity analysis, the percentage difference between Reese and Wright's analytical method and the elements up to PDA testing was 48.118%, and 10.808%. In the reduction analysis, the percentage difference between the empirical method and the elements up to the PDA test was 1.070%, and 0.061%. Based on these three methods, the results of the analysis of bearing capacity and the smallest settlement in value were obtained through PDA testing, finite element method and analytical method.
d. To get more accurate results when analyzing the bearing capacity and settlement of foundations utilizing analytical techniques like Reese and Wright as well as empirical approaches, comprehensive, representative data and a thorough comprehension of the facts are necessary. Comparing the study with other approaches, including Meyerhof and Poulos Davis, is also advised to assess its accuracy. To more realistically depict soil behavior in the field, it is advised to utilize a more thorough soil model, such Hardening Soil, as the finite element method using PLAXIS 2D software requires more comprehension due to its complexity.

REFERENCES

[1] R. Simanjuntak, Roesyanto, and S. E. Harahapan, “Analisis Daya Dukung Lateral Bored Pile Ø 80 Cm dengan Menggunakan Uji Beban Lateral dan Menggunakan Metode Elemen Hingga pada Proyek Menara BRI - Medan ,” *Jurnal Syntax Admiration*, vol. 5, no. 8, pp. 3130–3137, Aug. 2024.

[2] R. Aseanto and A. Sanjaya, “Analysis of Carrying Capacity of the Bored Pile Foundation in Cibubur Transpark Project,” *Journal of World Conference* , vol. 2, no. 3, pp. 63–68, May 2020.

[3] B. R. Kasmana, G. P. Artiani, and L. Darmiyanti, “Analisis Daya Dukung Pondasi Borepile Pada Proyek PembangunanFasilitas Perkeretaapian Manggarai -Jatinegara,” *Gudang Jurnal Multidisiplin Ilmu*, vol. 2, no. 8, pp. 117–124, Aug. 2024.

[4] B. M. Das, N. Endah, and I. B. Mochtar, *Mekanika Tanah (Prinsip-prinsip Rekayasa Geoteknis)*, 1st ed. Surabaya: Erlangga, 1995.

[5] M. S. Putri, Y. Apriyanti, and F. Fahriani, “Analisis Perbandingan Daya Dukung dan Penurunan Tiang Pancang Tunggal dengan Metode Statik dan Uji Beban ,” in *Prosiding Seminar Nasional Penelitian & Pengabdian pada Masyarakat*, Pangkalpinang, 2018, pp. 210–215.
[6] D. S. Hutapea, Roesyanto, and R. Iskandar, “Analisis Daya Dukung dan Penurunan Pondasi Tiang Bor dengan Plaxis 3D terhadap Hasil Loading Test,” *Jurnal Syntax Admiration*, vol. 2, no. 6, 2021.
[7] D. Prasetya and M. A. Hadi, “Identifikasi Pengujian Pile Driving Analyzer Pier 51A Pada Proyek Pembangunan Tol Yogyakarta – Bawen ,” *Proceeding Civil Engineering Research Forum*, vol. 3, no. 1, pp. 248–258, 2023.
[8] B. M. Das, *Shallow Foundations: Bearing Capacity and Settlement*, 3rd ed. US: Taylor & Francis, 2007.
[9] (BSN) Badan Standarisasi Nasional, “SNI 4153-2008 Cara Uji Penetrasi Lapangan dengan SPT,” Jakarta, 2008.
[10] E. Tanuwijaya, A. Kawanda, and H. Wijaya, “Studi Korelasi Nilai Tahanan Konus Sondir terhadap Parameter Tanah pada Proyek di Jakarta Barat,” *Jurnal Mitra Teknik Sipil*, vol. 2, no. 4, pp. 169–176, 2019.
[11] S. Prakash and H. D. Dharma, *Pile Foundations in Engineering Practice* . Canada : A Wiley-INterscience Publication, 2008.
[12] F. S. Darmawan and K. I. Sari, “Analisis Daya Dukung Pondasi Bored Pile Diameter 0,8 M Pada Proyek Gedung Menara BRI Jalan Putri Hijau, Medan,” *Buletin Utama Teknik* , vol. 18, no. 1, pp. 85–90, Sep. 2022.
[13] S. Dandagawhal, “Settlement Analysis of Pile Foundation Using PLAXIS 2D,” *International Journal of Science and Research (IJSR)* , vol. 8, no. 9, pp. 1706–1714, Sep. 2018.
[14] PLAXIS 2D, “General Information Manual ,” May 2024.
[15] B. A. Salahudeen and J. A. Sadeeq, “Evaluation of Bearing Capacity and Settlement of Foundations ,” *Leonardo Electronic Journal of Practices and Technologies* , no. 29, pp. 93–114, Jul. 2016.
[16] T. Ahmed, “Feasibility of Pile Driving Analyzer for Pile On Rock ,” Georgia Southern University , Georgia , 2024.
[17] PLAXIS 2D, “Reference Manual 2D ,” May 2024.